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A method for determination of upper extremity kinematics☆

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Abstract

Kinematic analysis of the upper extremity has been conducted using a wide variety of techniques, philosophies, and analytic methods. We describe a simple, marker-based three-dimensional video analytic technique that borrows concepts from lower extremity kinematic analysis. A sequential rotation order about orthogonal axes is described, although alternate methods are examined as well. The method has been verified by application to a mechanical model. In certain positions, gimbal lock may occur, and a different sequence of rotational decomposition may be required. Agreement on standardization of technique would assist in the dissemination of upper extremity scientific data. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The measurement of three-dimensional kinematics of the upper extremity has generally not received as much scientific attention as that of the lower limb. Upper limb motion may be rapid, and is spatially complex, particularly at the shoulder. This makes the use of markers attached to wands, which have been used for rotational measurement in lower extremity models, cumbersome, prone to interference with other limb segments, and subject to inaccuracies from soft-tissue oscillations and inertial effects. A measurement philosophy accommodating these restrictions needs to balance practicality with accuracy.

Modeling of movement of the wrist and elbow is relatively simple, since both can be represented as two-degrees-of-freedom joints. However, the shoulder joint complex is an articulation that defies simple kinematic description. It consists of two separate articulations, with scapulothoracic and glenohumeral components. Accurate determination of scapular position is difficult without skeletal pins, time-consuming palpation, or complex imaging techniques that are potentially invasive, expensive and impractical in most research settings [1–5]. The lack of a simple, non-invasive way of locating the scapula suggests that measurement of upper arm position relative to the trunk is a more practical goal than accurate individual measurement of glenohumeral and scapulothoracic motion in most experimental settings. This approach has been conceptually supported by other investigators [5].

The range of shoulder mobility is so great that interpretation of three-dimensional motion is non-intuitive in many circumstances [6]. This has resulted in a variety of descriptive methods with different coordinate axis definitions and different three-dimensional motion sequences, often reflecting the discipline of the investigator rather than an attempt to standardize based on logic or convention (Table 1). Thus, there is no consensus on either the specifics of local coordinate systems or on the sequence of movements to describe upper limb position.

We describe a three-dimensional system of upper extremity analysis using retroreflective skin markers that follows philosophical and computational principles borrowed from lower extremity kinematic analysis. Its advantages are ease of use and familiarity to clinicians. The analytical rotation sequence that we routinely use can be modified if required for specific test situations.

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Table 1
Summary of some recent upper extremity kinematic analysis methods

Author	Axes			Rotation sequence	Method
	X	Y	Z	1st 2nd 3rd	
An et al. (1991) [13]	inf	lat	ant	XZ′X″	Magnetic tracking
Bao and Willems (1999) [17]	ant	lat	sup	Unspecified	LED's with wand frame
Davis et al. (1998) [14]	inf	lat	ant	XZ′X″	Surface markers
DeGroot (1997) [1]	lat	ant	sup	YZ′Y″	Surface markers
Dillman et al. (1993) [18]	ant	lat	inf	Unspecified; projectional?	Surface markers
Schmidt et al. (1999) [10]	sup	lat	ant	YZ′X″	Surface markers with corrective algorithm
Van der Helm and Pronk (1995) [5]	lat	inf	ant	XY′Z″/YZ′Y″	Surface markers and scapular palpation
Veeger et al. (1997) [7]	lat	ant	sup	Unspecified	Magnetic tracking uses scapular reference plane
Wang et al. (1998) [19]	lat	ant	sup	ZY′X″	Surface markers
Whiting et al. (1998) [20]	Undefined			Unspecified	Single lateral surface markers over estimated joint centers
Wu and Cavanagh (1995) [15]	ant	lat	sup	XY′Z″	Undefined

See reference section for complete reference.

2. Materials and methods

2.1. The model

The biomechanical model consists of 10 segments (head, neck, shoulder girdle, left upper arm, right upper arm, left lower arm, right lower arm, left hand, right hand, pelvis) whose local coordinate systems are used to calculate upper extremity motion (Table 2). All joints are assumed to have fixed centers of rotation, for ease of calculation. The wrist joint is modeled as a universal (saddle) joint with two-degrees-of-freedom, where wrist movement occurs in flexion-extension and radio-ulnar deviation. In keeping with clinical convention, wrist movement is represented by movement between the hand and forearm segments, determined by a vector connecting the geometric wrist center and the calculated elbow center. The elbow joint is modeled as a rotating-hinge joint with two-degrees-of-freedom (constrained varus and valgus), with a single joint center in the distal humerus. Forearm pronation and supination are modeled as rotation about an axis connecting the elbow center and distal ulna. The shoulder joint is modeled as a ball and socket joint with three-degrees-of-freedom, located in the center of the humeral head. Movement is calculated between the humerus and the trunk, and scapular contribution to shoulder motion is ignored. These are similar to conventions adopted by Veeger et al. [7].

2.2. Marker positions

We have chosen a standard three-dimensional video-based technique using retroreflective markers attached to the subject (Fig. 1). Eighteen markers (1 in. diameter) are placed over prominent bony landmarks of the upper extremity that are easily identifiable and reproducible, where subcutaneous tissue is thin and relatively fixed to the underlying skeleton, thereby minimizing marker movement artifact. We do not employ a specific mathematical algorithm to correct for motion of skin over skeletal structures. Rotational wands are not used.

2.3. Determination of segment geometry and orientation

Each segment is defined by a proximal and distal point located at a joint center, and a third non-collinear point for rotational orientation. Joint positions are calculated as offsets from selected skin sites of surface markers. The magnitude of the specific offsets is ex-

Table 2
Segment definitions used for biomechanical model

Moving segment	Reference segment	Designated joint movement
Head	Neck	Head
Neck	Shoulder girdle	Neck
Shoulder girdle	Pelvis	Trunk
Left upper arm	Trunk	L shoulder
Right upper arm	Trunk	R shoulder
Left lower arm (elbow center to distal ulna)	Left upper arm	L elbow
Right lower arm (elbow center to distal ulna)	Right upper Aam	R elbow
Left hand	Left lower arm (elbow center to wrist center)	L wrist
Right hand	Right lower arm (elbow center to wrist center)	L wrist
Pelvis	Global (Laboratory)	Pelvic tilt, obliquity, rotation

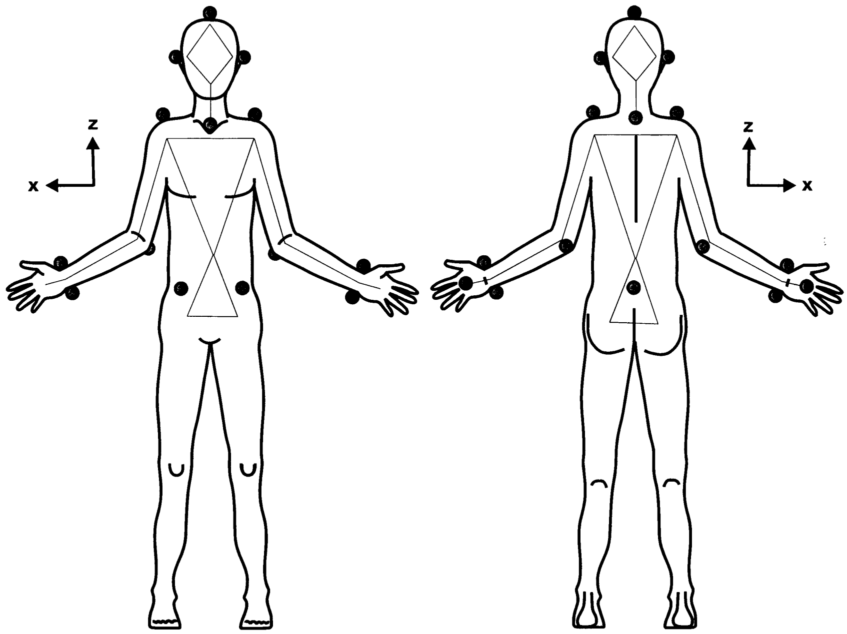

Fig. 1. Diagram of marker placement for kinematic analysis. The thin lines represent segments connecting calculated joint centers (see text).

pressed as a fraction of the distance between individual markers, as determined from measurements of a single normal male adult. This method allows rapid analysis without requiring specific measurements for individual subjects. In the lower extremity, such calculations have been used to estimate hip joint center location as a function of the distance between pelvic surface markers [8].

Magnitudes of offsets were determined by direct measurement of both limbs of an adult and a pediatric (estimated age six years) skeleton, and by anatomic data available in the literature, based on seven cadavers [9]. It was necessary to adapt these measurements to our trunk–humerus model since available anthropomorphic measurements have been made on isolated shoulder girdle specimens with global coordinate axes based in the plane of the scapula. Statistical data on skin thickness are not available, but surface marker sites were selected in regions of thin subcutaneous tissue (acromio-clavicular joint, olecranon, radial and ulnar styloid) to minimize inaccuracies associated with this variable. The relative displacements are summarized in Table 3. Note that an additional allowance for marker radius should be added for accuracy.

Embedded coordinate systems are determined for each segment from three associated non-collinear points. If a joint is mechanically constrained, as is the elbow, the plane defined by the long axes of the two segments can define the rotational position of one of them as long as the three joints or their associated external markers are not collinear. This allows the slightly flexed elbow to be used to determine humeral rotation, eliminating the need for rotational wands or markers placed on the mobile mid-segment skin, and the correction algorithms that are necessary for this method of analysis [10].

A special circumstance occurs if the elbow hyperextends. The olecranon marker, which generally is posterior to a line connecting the shoulder and wrist centers, becomes collinear with them. This makes calculation of rotational orientation impossible in the upper and lower arm segments. Because hyperextension is a rare occurrence in daily living activities, we feel this is an acceptable compromise for the simplicity and accuracy of marker placement. In specific circumstances where hyperextension occurs, local interpolation or alternate rotational orientation markers could be used [10].

In some circumstances, a specific axis or plane corresponds best to palpable bony landmarks. For example, the initial estimation of the forward axis of the base of the neck lies in the segmental sagittal plane along a line connecting the tip of C7 with the jugular notch of the manubrium (sternum). This adds an anatomic inclination to the local imbedded coordinate systems (e.g. the xy plane is not horizontal); the orientation of the resulting axes may not correspond to the axes selected for angular displacements in the biomechanical model. In such circumstances, the local coordinate system is rotated to either a more appropriate anatomical orientation or to the laboratory global coordinate system before intersegmental rotations are calculated.

2.4. Rotation sequence

In the lower extremity, medical clinicians empirically think in the sequence flexion-abduction-axial rotation.

Upper extremity movement is far less likely to be sagittal, but the sequence is easy to remember and logical for anyone who deals with medical subjects. For this reason, we define embedded right-hand coordinate systems with the X axis directed laterally to the right, Y axis directed forward (anteriorly), and Z axis directed upward (superiorly). This allows the Eulerian sequence about the axes X, Y, and Z to correspond to forward flexion, abduction, and axial rotation. We use this as a general default sequence; for specific analyses, other rotation sequences may sometimes be more appropriate.

Base position is defined as the anatomic position. This is a standardized, internationally recognized position with the subject standing, arms extended at the side, with forearms fully supinated and palms forward.

3. Algorithm accuracy and system stability

A rigid aluminum frame articulated model of the shoulder girdle and upper extremity was used for analysis of algorithm accuracy and system stability (lack of 'noise'). The device was placed in the motion system's field of view and a sequence of shoulder positions based on rotations about multiple axes was recorded (e.g. flexion followed by abduction followed by external rotation). Calculated and observed model angular displacements were consistent, with maximum standard deviations of calculated angles during one second (60 frames) always less than 1°.

Elbow flexion and pronation were constant, because the arm and forearm segments were moved in a unit as the shoulder was repositioned. During eight 60-frame trials, the maximum standard deviation in elbow position was 1.8°, which reflects the inherent resolution limit of the optical system as the one in. diameter retroreflective markers are rotated through space.

With the shoulder abducted 90°, the Z (axial rotation) axis of the humeral segment coincides with the X (flexion-extension) axis of the shoulder in its initial position. In this position, the decomposition of the initial angle of the rotation sequence (in this case, flexion) becomes indeterminate (gimbal lock). Analysis of the linked model in the 89–91° range of abduction yielded unreliable estimates for initial flexion angle, as well as large standard deviations (6° or more) of calculated angles over 60 frames of static data collection. These data reflect the instability of the analytic model in or near regions of gimbal lock. In practical analysis, such artifacts are usually obvious and easy to locate. If the arc of motion in a specific experiment includes large abduction angles, alternate rotation sequences might be used for the analysis. Examples of this might include movement in a horizontal plane near shoulder height, or throwing a ball.

4. Sensitivity to marker position and joint center calculations

Offsets from surface markers that are calculated as a fraction of segment length are frequently used for estimation of hip joint centers, and accuracy has been studied [8]. There are no similar statistical data to support our method of upper extremity joint center calculations by offsets from surface markers. Errors could be anticipated due to marker misplacement, to relative movement between markers and bony landmarks as the skin moves, and to inaccuracies in the

Table 3
Offsets to joint centers used in this study

Joint	Reference marker	Reference segment	Displacement to joint center		
			Lateral (x)	Anterior(y)	Superior(z)
Head	Ears	Inter-ear distance	Midpoint		
Neck top	Head center	Head center—head top	0	0	−100%
Neck bottom	C7	C7-sternum	Midpoint		
Right hip	R ASIS	R ASIS–L ASIS	−22%	−18%	−34%
Left hip	L ASIS	L ASIS–R ASIS	−22%	−18%	−34%
Right shoulder	R A–C joint	R A–C joint-L A–C joint	0	0	−17%
Left shoulder	L A–C joint	L A–C joint-R A–C joint	0	0	−17%
Right elbow	R olecranon	R olecranon—R dist.ulna	0	6%	13%
Left elbow	L olecranon	L olecranon—L dist ulna	0	6%	13%
Right wrist	R dist. Radius	R dist radius—R dist ulna	Midpoint		
Left wrist	L dist. Radius	L dist radius—L dist ulna	Midpoint		
Right hand	R dors. 3rd MCP joint	MCP–R wrist joint center	0	30%	0
Left hand	R dors. 3rd MCP joint	MCP–L wrist joint center	0	30%	0

Offsets are expressed as a percentage of reference segment length. The measurements are from the skin position of the marker, and additional displacement should be added to accommodate the physical size of the marker itself.

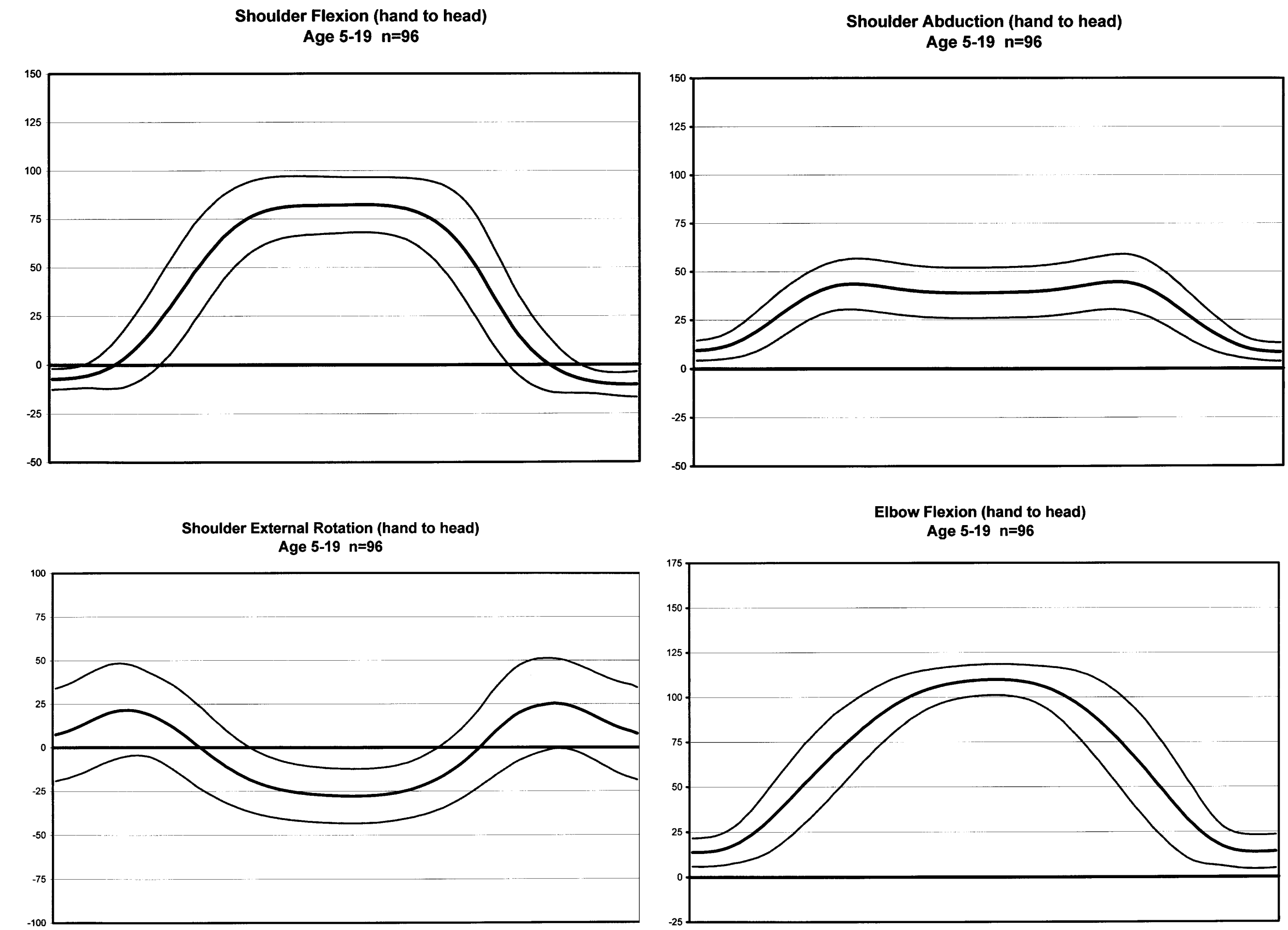

Fig. 2. Representative graphs of three-dimensional motion of 96 limb motion studies in 48 normal children, age 5–19 years, performing a task of raising the hand to the top of the head. Graphs show mean (dark line) and ± one standard deviation (thinner line). The horizontal axis reflects time. The data has been 'normalized' to represent the start and finish of the activity, which vary with individual subjects. (A) Shoulder flexion. (B) Shoulder abduction. (C) Shoulder external rotation. (D) Elbow flexion.

displacement algorithm for calculation of joint centers. To study the sensitivity of the method to inaccuracies in joint center estimation, we perturbed the calculated position of the model shoulder joint center by ± 1.0 cm along each of the three coordinate axes, and recalculated the shoulder position. The resulting variation in shoulder angles was always within 5°. Shoulder flexion was affected by anterior–posterior joint center displacements (1–3°). Shoulder abduction was affected by medial–lateral displacements (3–5°). Shoulder (humeral) axial rotation was not affected by any joint displacements.

Since the articulated model was half adult size, we performed similar shoulder joint center perturbations of ± 2.0 cm on actual subject data, with the subject moving the arm through complex spatial motions. We selected this measurement because it exceeds one standard deviation of shoulder displacement data derived from cadaveric measurements made by van der Helm et al. [9], which are available on the web site noted in the cited reference. The outcome was similar, but correlation between specific directional displacement and affected calculated angle was not present (for example, a shoulder joint center perturbation along the X axis did not purely correlate with change in measured shoulder abduction/adduction angle). Thus, we feel that potential inaccuracies in joint center calculations will have a minimal, acceptable effect on angle calculations with most movements.

5. Example

Fig. 2(A–D) depicts selected kinematics of the upper extremity during the activity of raising the arm from the side to touch the top of the head, and then returning it to the side. The data were collected from 94 limbs in 47 children, age 5–19 years, voluntarily performing the task under a prospective protocol approved by the University of California, Davis, Medical Center's Human Subjects Review Committee. The mean and plus or minus one standard deviation are shown.

For the four motions depicted, maximum standard deviation was 25°. This implies both reproducibility of the measurement method and uniformity in movement strategies adopted by the subjects.

6. Discussion

Because of the wide diversity in axis designation and rotational sequence, research on shoulder kinematics is particularly difficult to evaluate and compare [11,12]. Basically, there are two methods for expressing results that are mathematically equivalent but which convey different information to the investigator. One method, as described here, involves sequential rotations about three orthogonal axes; the variability between investigators can be improved if authors adopt certain arbitrary conventions of axis designation and rotational sequence (1st 2nd 3rd: $XY'Z''$). The second method [13,14] rotates the humerus along its longitudinal axis to determine the plane of abduction, then abducts the arm and rotates the humerus along its longitudinal axis once again to achieve final displacement (using our axis designation, the rotation sequence is $ZY'Z''$ or, alternatively, $ZX'Z''$).

Suggestions by the International Society of Biomechanics (ISB) for a standardized method for reporting experimental data [15], and the response to those attempts from a strict mechanical engineering viewpoint [16], highlight the strong differences of opinion between investigators. Many of these differences arise because of the separate scientific discipline of individual investigators. For example, we feel that the arbitrary designation of axes in the ISB recommendations is based more on historical use and two-dimensional consistency than on modern considerations and clinical clarity. We feel for the reasons detailed above that our approach may have appeal because it is entails an easy-to-use and easy-to remember clinical rotation sequence for data analysis and presentation.

There are limitations to the accuracy of any analysis of motion by indirect surface methods, even when the accuracy of three-dimensional marker tracking is assumed. Our model describes movement of the humerus relative to the trunk, which is not an accurate representation of true shoulder anatomy or function. We do not know how much elbow flexion is necessary for accurate determination of humeral rotation, although use of a posterior olecranon marker and the presence of physiologic elbow flexion posture minimizes this problem in most circumstances. Skin movement is a constant problem with all marker-based motion measurements, and the degree to which it affects accuracy is unknown. There is little statistical information to support the displacements between markers and joint centers that were used in this study, but we have attempted to address this issue by examining the effect of inaccuracies on joint center estimation, and we feel that the described offsets produce acceptable measurement accuracy for practical analysis. There is no available data on joint center location in children, and we are forced to use extrapolations from modest adult measurements to perform movement analysis in immature subjects. Gimbal lock can be an unrecognized problem, leading to angular measurements whose interpretation is difficult and nonintuitive. Despite the multiple limitations, we believe that investigators who take these issues into account can achieve reliable, reproducible results of appropriate accuracy and practical utility.

With the complexity of upper extremity movement, there must be a proactive decision by investigators to use the method that best conveys meaningful data in an understandable form. However, it makes little sense for researchers to continue to use such a diversity of methods for expressing and distributing their data. The minimum requirement for reporting should be a clear description of axes (preferably with pictures), rotation sequences, and model assumptions. It is our hope that a trend toward standardization of analytic techniques leads to an increase in communication and learning about upper extremity kinematics.

7. Summary

A method of three-dimensional kinematic analysis of the upper extremity is presented, using surface markers and current video data collection techniques. The method has been verified, and sensitivity to calculation errors has been quantified. The philosophical and practical issues involved are discussed, and examples of data output are presented. We recommend that investigators in this area adopt a standardized approach to kinematic analysis so that uniformity and sharing of data is simpler and more effective.

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