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TECHNICAL NOTE

PARAMETERS FOR MODELING THE UPPER EXTREMITY

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Abstract—The purpose of this paper was to provide parameters for the development of a musculoskeletal model of the upper extremity. Five upper extremity specimens were obtained from four fresh cadavers. Anthropometric measures were obtained for each cadaver. Segment inertial parameters were estimated for each specimen from anthropometric measures of the cadaver from which the specimen was obtained. The three-dimensional kinematics of the humerus, ulna, and radius in different movements of the glenohumeral, humeroulnar and ulnoradial joints were measured for each specimen using of the 3Space™ tracking system (Isotrack, Polhemus). The instantaneous rotation center of the glenohumeral joint and the instantaneous rotation axes of elbow flexion and forearm pronation were determined for each specimen from the kinematic data. The specimens were dissected and the muscle origins and insertions and bony structures needed in upper extremity modeling were digitized using the 3Space™ system. The shapes of muscle origins and insertions were estimated. Muscle length, volume and pennation angle were measured for the estimation of physiological cross-sectional areas of each muscle. The results, which are given for one specimen, showed that the rotation center of the glenohumeral joint was very close to the geometric center of the joint with a mean distance of 4 mm. The mean angle between the flexion–extension and pro-supination axes of the elbow joint was 94°. The minimum distance between these two axes was about 4 mm. © 1997 Elsevier Science Ltd

Keywords: Biomechanics; Musculoskeletal model; Upper extremity; Shoulder; Elbow.

INTRODUCTION

Morphological measures are important parameters in modeling musculoskeletal systems. Many studies have been conducted to obtain morphological parameters for developing biomechanical models of different human musculoskeletal systems (Lieber, 1992; Yamagushi *et al.*, 1990). However, only few studies have focused on the upper extremity. There is a lack of information on three-dimensional locations and orientations of muscle attachments and the orientation of axes of rotations of upper extremity joints, because of the difficulty in measurement. Högfors *et al.* (1987), Wood *et al.* (1989), Johnson (1990) and Van der Helm *et al.* (1992) reported coordinates of muscle attachment sites for the shoulder complex. Wood *et al.* (1989) also reported three-dimensional coordinates of attachment sites for selected arm muscles obtained from one specimen. However, they reported each muscle attachment site as a single point. Other studies with focus on the morphological parameters of upper extremities were limited to the determination of moment arms of selected arm muscles in selected movements (Amis *et al.*, 1979; An *et al.*, 1981).

Qualitative descriptions of the locations of axes or centers of rotations of upper extremity joints were given in several studies. Poppen and Walker (1976) described the center of rotation of the glenohumeral joint. Morrey and Chao (1976), Youm *et al.* (1979), and Deland *et al.* (1987) described the axes of rotation for the elbow joint. No report was found on quantitative descriptions of the locations of these axes and centers of rotation of the upper extremity.

The purpose of this study was to determine those parameters for modeling the upper extremity. These parameters included the three-dimensional locations of muscle attachment sites, muscle volumes, muscle lengths, pennation angles, the center of rotation for the glenohumeral joint, and axes of rotation for the humeroulnar and radioulnar joints. A complete set of these parameters was obtained from each specimen. In addition, segment inertial parameters were estimated for each specimen from anthropometric measures.

METHODS

Five upper extremity specimens (four right and one left arm) were obtained from four fresh cadavers with the approval of the Mayo Clinic Internal Review Board. Body weight and height, lengths and circumferences of the forearm and upper arm, and the length and width of the hand were measured for each specimen and used for the calculation of inertia parameters for the arm, forearm and hand. The mass and the location of the center of mass were estimated for each segment from associated anthropometric measures using regression equations developed by Clauser *et al.* (1969). Moments of inertia about the three principal axes were also estimated for each segment from the associated anthropometric measures using regression equations developed by Yeadon and Morlock (1989) based on the data reported by Chandler *et al.* (1975) (Table 1). After the anthropometry measurements, each upper extremity was disarticulated from the thorax with all scapulohumeral muscles intact.

A magnetic position and orientation tracking system (3Space™ Isotrack™ System) was used to collect three-dimensional position and orientation data in this study. The application and accuracy of this system in biomechanical studies on human body motion has been described by An *et al.* (1988). The 3Space™ system used in this study consisted of a System Electronics Unit, a source, and four sensors. For accurate placements of the sensors, nylon sensor seats were fixed on the spine of the scapula and the shafts of humerus, ulna and radius. The upper extremity specimen was then mounted on a measuring board with the spine supported by the upper edge of the board (Fig. 1). Three 3Space™ sensors were placed on the sensor seats on the humerus, ulna and radius. To determine the location and orientation of the scapula, a fourth 3Space™ sensor was positioned on the proximal-lateral aspect of the spine of the scapula close to the Angulus Acromialis (Fig. 1).

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Table 1. Antropometric characteristics and inertial parameters for all specimen. The center of mass positions were defined relative to their proximal landmarks. The moments of inertia are expressed as a moment of inertia about the two transverse axes and the longitudinal axis of each segment

	#1_r	#2_r	#2_l	#3_r	*#4_r*	Mean
Gender	Male	Male	*	Male	*Male*	
Age (yr)	75	81	*	70	*48*	68.5
Mass (kg)	77	83	*	62	*98*	80.0
Stature (cm)	183	177	*	163	*191*	178.5
Upper arm length† (cm)	34	34	33	33.5	*36*	34.1
Forearm length‡ (cm)	25	27	27.5	25	*28*	26.5
Segment mass (kg)						
Upper arm	1.91	1.57	1.48	1.40	*2.57*	1.79
Forearm	1.22	1.15	1.15	0.86	*1.09*	1.09
Hand	0.50	0.46	0.49	0.39	*0.46*	0.46
Segment mass position (prox.) (cm)						
Upper arm	24.0	21.8	20.1	16.9	*17.4*	20.1
Forearm	10.1	10.4	11.0	9.5	*11.2*	10.5
Hand	4.5	4.1	4.5	4.1	*4.5*	4.3
Transversal moments of inertia (kg cm^2)						
Upper arm	147.60	138.22	101.84	91.54	*181.18*	132.08
Forearm	55.46	60.08	61.28	38.13	*66.73*	56.34
Hand	22.44	31.48	41.93	20.38	*28.24*	28.89
Longitudinal moments of inertia (kg cm^2)						
Upper arm	23.74	13.51	11.77	9.62	*24.82*	16.69
Forearm	8.73	7.26	6.94	4.33	*7.52*	6.96
Hand	3.78	4.62	5.32	2.83	*3.77*	4.07

* Values have not been included in the calculated means.
† Defined as the distance between Acromioclavicular joint (AC) and Lateral Epicondyle (EL) (Clauser *et al.*, 1969).
‡ Defined as the distance between EL and Processus Styloideus Ulnae (US).

The reference frame of the source was used as the global reference frame G with the z_g-axis pointing upward, the x_g-axis is parallel to the surface of the measuring board and pointing to the lateral side of the specimen, and the y_g-axis pointing from the posterior surface to the anterior surface of the scapula. The spine of the scapula was approximately parallel to the x_g-axis of G (Fig. 1). The upper extremity specimen was considered to be in the standard position when the elbow was fully extended and the forearm was supinated.

Sensors' positions and orientations in five selected passive arm motions were recorded at a sampling frequency of 10 Hz. These five passive motions included abduction–adduction, flexion–extension, and internal–external rotation of the humerus about the glenohumeral joint, flexion–extension of the forearm about the elbow joint, and forearm pronation–supination. Three trials were conducted for each motion. Two cycles through the full range of motion was completed in 15 s in each trial.

After the passive motion test, the specimen was dissected. Muscles were detached from their attachment sites, and joints were disarticulated. Selected anatomical landmarks, muscle attachment sites, and morphological shapes (Table 2) were digitized relative to the local reference frame L of the sensor on the associated segment.

Each dissected muscle was weighed using a scale with an accuracy of 0.1 g. Muscle volume was measured using the immersion method and with an accuracy of 1 ml. Tendons were included in the measuring process. Belly lengths and pennation angles were also measured. The belly length of a muscle was defined as the distance between the most proximal musculotendinous conjunction and the most distal musculotendinous conjunction of the muscle. Pennation angles were defined as the angles between muscle fibers and the straight line between the proximal and distal musculotendinous conjunctions of the muscle, and measured using a goniometer. From muscle mass, volume, belly length and pennation angle, physiological cross-sectional area (PCSA) were calculated. PCSA was estimated in three different ways: from mass and belly length corrected for pennation angle; from volume and belly length, corrected for pennation angle and as the ratio between volume and belly length. The coordinates of each muscle attachment site or bony landmark in the associated sensor reference frame L_s were transformed to G using

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = [R_s]^{\mathrm{T}} \begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} - \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix}, \quad (1)$$

where x_g, y_g, and z_g are the coordinates of the given muscle attachment site or bony landmarks in G, $[R_s]$ is the direction cosine matrix of sensor s in G; x_l, y_l, and z_l are the coordinate of the given muscle attachment site of bony landmarks in L_s; and x_s, y_s and z_s are the coordinates of origin of L_s in G.

The coordinates of a muscle attachment site or bony landmark in G were expressed as polynomial functions of relative length t of the muscle attachment site or bony landmark as described by Van der Helm *et al.* (1992)

$$x_g = \sum_{n=0}^{N} a_n t^n, \qquad y_g = \sum_{n=0}^{N} b_n t^n, \qquad z_g = \sum_{n=0}^{N} c_n t^n, \quad (2a)$$

where a_n, b_n and c_n are polynomial parameters estimated using least-squares procedures. The mean resultant error in x_g, y_g, and z_g was expressed as

$$e = \frac{1}{M} \sum_{m=1}^{M} \mathrm{norm} \begin{bmatrix} x_{g,m} - x'_{g,m} \\ y_{g,m} - y'_{g,m} \\ z_{g,m} - z'_{g,m} \end{bmatrix}, \quad (2b)$$

where M is the total number of digitized points for a given attachment site or bony landmark; $x_{g,m}$, $y_{g,m}$, and $z_{g,m}$ are estimated three-dimensional coordinates of the mth point in a given attachment site or bony landmarks, and $x'_{g,m}$, $y'_{g,m}$ and $z'_{g,m}$ are measured coordinates of the mth point in the given attachment site or bony landmarks. The orders of

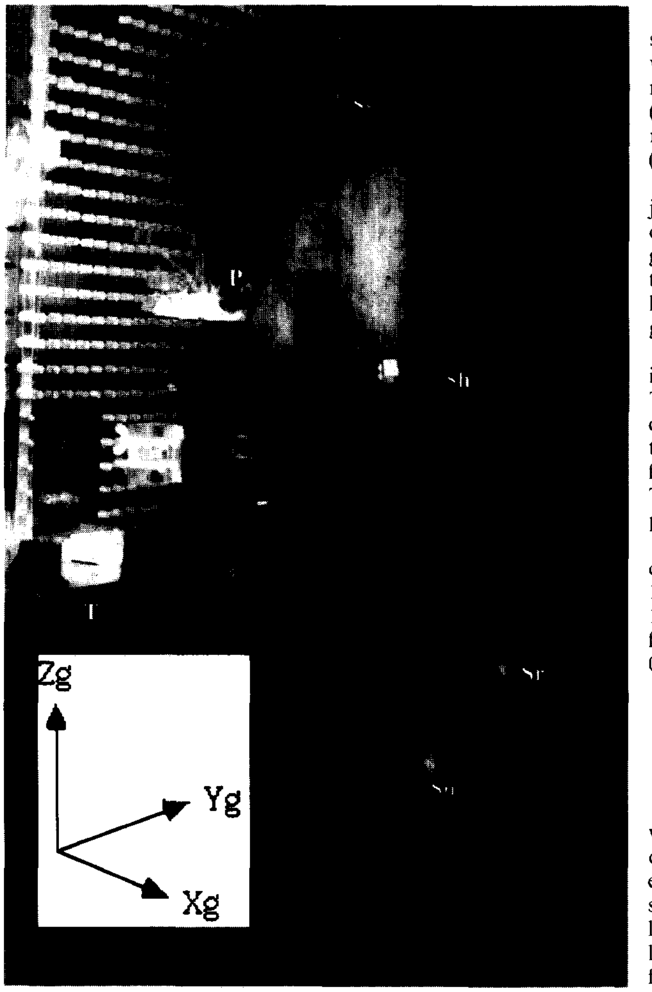

Fig. 1. Illustration of the experimental set-up. The scapula is fixed with its dorsal surface to a perspex plate perpendicular to the measuring board (P). The transmitter (T) is fastened to the measuring table. S_s, S_h, S_u and S_r indicate the sensor seat (S_s) and seats + sensors.

polynomials were either zero or one. A zero-order polynomial represents a point while a first-order polynomial represents a straight line. A mean resultant error greater than 1 cm for the zero-order polynomials indicated the use of a first-order polynomial. The coordinates of the bicipital sulcus were expressed as second-order polynomials.

The glenoid fossa and humeral head were modeled as spheres. The elbow joint, the proximal part of the radius and the distal end of the ulna were modeled as cylinders. These geometrical shapes were fitted using the algorithms described by Van der Helm *et al.* (1992). Instantaneous helical axes (IHA) of each joint were determined from the recorded motion data of the associated segments using an algorithm described by Woltring (1990). From these IHAs, the pivot point, P_{opt}, and optimal direction vectors, V_{opt}, were calculated, again following Woltring (1990). The error of estimations were expressed as

$$e = \frac{1}{N}\sum_{i=1}^{N} \text{norm}(P_{opt} - P_i) \tag{3a}$$

$$e = \frac{1}{N}\sum_{i=1}^{N} \arccos(V_{opt} \cdot V_i'). \tag{3b}$$

RESULTS

The four specimens that became available for dissection weighed between 62 and 98 kg and had a range in stature between 1.63 and 1.91 m. As a consequence, the estimated inertial parameters varied also, especially in estimates of the moments of inertia (Table 1).

Although data for all four specimen are available, only the data for specimen #4_r are presented here. Most of the muscle attachment sites were single points ($N = 0$). In these cases, a_0, b_0, and c_0 were simply the means of the recorded coordinates of the given muscle attachment site (Table 2). However, some muscle attachment sites, such as the origin of medial triceps on humerus, were apparently straight lines ($N = 1$) (Table 2).

The kinematically determined rotation center of the glenohumeral joint could be described as an estimated optimal rotation center with coordinates very close to both the estimated geometric centers of the glenoid fossa and the humeral head (Table 3). The estimated radius of the glenoid fossa and humeral head was very similar. The center of the humeral head was slightly lower and dorsolateral from the center of glenoid fossa.

The IHAs for flexion–extension were found to show some variation in the location and direction during the flexion movement (Fig. 2A). The orientation of the IHA of the forearm pronation–supination changed very little through the range of the forearm pronation–supination (Fig. 2B). However, a mean axis was obtained for each of these two forearm motions for each specimen with relatively low errors (Table 3). The mean axes for these two forearm motions were approximately perpendicular to each other and about 4 mm away.

The measured muscle masses and volumes were proportional to each other and consistent with reported values for muscle density (ρ = 1060 kg/m^3, Table 4). The pennation angles of most muscles were below 15°. As a result, the three estimations for PCSA differed only marginally for those muscles. Between muscles, the PCSA values varied strongly: 0.96 cm^2 for Anconeus and 5.30 cm^2 for Brachialis [Table 4, PCSA (1)].

DISCUSSION

The coordinates of muscle attachment sites and bony landmarks were expressed in a global reference frame. This choice of expressing data allows for the re-expression of these data in different local reference frames, if necessary with the use of landmarks on other (adjacent) segments. This is important for the humerus, ulna and radius where local coordinate systems are often defined with landmarks that are not located on the segment itself (Veeger *et al.*, 1993). In the global reference frame, the scapula was fixed against the measuring board with the dorsal plane of the scapula in the x_g–z_g plane and its spine almost parallel to the x_g-axis. This does not conform the standard anatomical position. When compared to the average resting position (Pronk, 1991), the scapula is rotated about −45° around the z_g-axis and 20° around the x_g-axis. However, since the local reference frame of the scapula can be defined with local landmarks (Johnson *et al.*, 1993), this deviation from the resting position is only of minor importance.

When modeling the upper extremity, it is common to define joint axes based on the assumed geometry of anatomical landmarks. However, there is a lack of quantitative descriptions of the locations of those landmarks and the validation of the assumptions about the geometrical shapes of those landmarks. The results for this study indicated that it seems reasonable to model the glenohumeral joint as a ball-and-socket joint with three degrees of freedom and center of rotation in the geometric center of the joint. These results were consistent with those reported by Högfors *et al.* (1987) and Van der Helm *et al.* (1989). The location of the center of rotation of the glenohumeral joint obtained in this study was in agreement with that described by Poppen and Walker (1976). They reported that the center of rotation of the glenohumeral joint was about 6 mm from its geometric center.

The combination of the estimated flexion–extension axis and prosupination axis in this study indicated that the axes are essentially perpendicular to each other (Table 3) and cross at a distance of 4 mm. The estimated elbow axis and elbow cylinder (Table 3) confirmed previous qualitative observations of a flexion–extension axis passing through the center of the trochlea and the capitulum humeri (Deland *et al.*, 1987; Morrey and Chao, 1976; Youm *et al.*, 1979). The suggestion by Morrey and Chao (1976) that the position of the axis is dependent on elbow angle, could not be confirmed. It thus seems reasonable to model the humeroulnar joint as a uniaxial joint.

It appeared that the pronation of the forearm took place around a tight axis (Fig. 2B), which runs through the radial head and the distal end of the ulna. This finding confirmed the previous work by several authors (Fick, 1911; Hollister *et al.*, 1994; Morrey and Chao, 1976; Youm *et al.*, 1979). The smallest distance between the center of the radial head and the axis of rotation was about 5 mm.

Table 2. Overview of the positions of anatomical landmarks and attachments for specimen #4_r. The x_g, y_g and z_g coordinates are expressed as functions of the relative length of the attachment site. Given are the coefficients a_n, b_n and c_n for $n = 0, \ldots, N$, that correspond with the t-values as defined in equation (2). e = estimated error [Equation (2)]

Scapula	n	X_g (cm)	Y_g (cm)	Z_g (cm)	e (cm)
Acromioclavicular joint (AC)	0	25.29	1.28	40.96	0.01
Angulus Acromialis (AA)	0	24.85	−1.93	39.22	0.01
Trigonum Spinae (TS)	0	12.87	1.47	36.92	0.01
Angulus Inferior (AI)	0	13.86	3.09	22.91	0.01
Biceps caput Longum	0	23.70	1.81	38.18	0.31
Biceps caput Breve	0	24.34	5.72	39.52	0.49
Coracobrachialis	0	24.27	5.54	39.33	0.39
Triceps caput Longum	0	23.97	1.96	34.53	
	1	−2.43	0.40	−2.13	0.11
Humerus		a (cm)	b (cm)	c (cm)	e (cm)
Epicondylus Lateralis (EL)	0	30.75	−1.13	5.18	0.02
Epicondylus Medialis (EM)	0	23.49	−0.90	5.31	0.01
Sulcus bicipitalis	0	27.03	5.01	36.98	
	1	0.16	−0.91	−6.90	
	2	−0.89	−0.67	2.10	0.16
Brachialis	0	26.79	1.24	23.38	
	1	0.74	−1.88	−14.86	1.27
Triceps caput Mediale	0	25.08	1.42	28.99	
	1	1.67	−3.87	−21.64	0.79
Triceps caput Laterale	0	26.93	1.36	31.95	
	1	0.22	−1.94	−10.04	0.61
Coracobrachialis	0	25.72	0.64	20.70	
	1	−0.07	−0.41	−2.64	0.07
Brachioradialis	0	27.89	−1.50	12.45	
	1	0.59	−0.16	−3.90	0.11
Anconeus	0	29.39	−1.50	4.35	0.66
Pronator Teres	0	24.57	−0.78	6.23	
	1	−0.29	0.06	−2.54	0.72
Supinator	0	30.29	0.05	4.10	0.37
Ulna					
Processus Styloideus Ulnae (US)	0	32.21	6.80	−21.60	0.03
Olecranon (OL)	0	25.78	−3.83	5.55	0.02
Brachialis	0	26.84	−0.37	0.62	0.84
Triceps	0	25.95	−3.53	5.08	0.50
Pronator Quadratus	0	30.32	5.00	−15.59	
	1	1.40	2.01	4.94	0.68
Anconeus	0	27.59	−2.82	3.54	
	1	1.09	1.04	−4.92	1.16
Pronator Teres	0	24.05	−0.71	3.83	0.24
Supinator	0	28.51	−1.33	2.31	
	1	1.08	0.86	−5.18	0.61
Radius					
Processus Styloideus radii (RS)	0	36.27	9.65	−20.43	0.02
Biceps	0	28.74	1.92	0.06	0.49
Brachioradialis	0	35.48	9.45	−18.96	0.04
Pronator Quadratus	0	34.65	7.29	−15.48	
	1	−1.02	0.71	−4.18	1.53
Pronator Teres	0	33.00	4.41	−8.23	
	1	0.74	0.95	−2.74	0.09
Supinator	0	29.69	1.03	2.86	
	1	1.76	2.15	−9.30	1.52

Physiological cross-section areas (PCSAs) are important parameters for determining relative force distributions in musculoskeletal system modeling. The PCSA of a given muscle can be directly measured (Veeger *et al.*, 1991) or indirectly estimated from the volume, mass, fiber length, and pennation angle of the muscle (Amis *et al.*, 1979; Cutts and Seedhom, 1993; Lieber, 1992; Yamaguchi, 1991). The muscle volumes, lengths, and pennation angles obtained in this study (Table 4) allow for different methods of calculation for PCSA. PCSA values are dependent on the chosen experimental and calculation methods. In addition, the PCSA for a given muscle shows inter-individual variation (Veeger *et al.*, 1991). However, a study by Cutts and Seedhom (1993) indicated that the use of PCSA obtained from cadaver data, in which fiber length is the parameter that is most susceptible to estimation errors, led to acceptable results when relative values are required. As a consequence, when PCSA is used for the determination of relative muscle contributions, the exact calculation procedure for PCSA is of lesser importance than the use of a consistent data set. To have a better estimate of relative muscle force contributions, PCSAs should be estimated using the same method and from the data of the same specimen.

Table 3. Overview of the estimated rotation center and rotation axes for specimen #4_r, based on instantaneous helical axis calculations. Vector $[P_x, P_y, P_z]$ is the location vector of the optimal pivot point P_{opt}. Vector $[V_x, V_y, V_z]$ is the unit direction vector of the rotation axes. Also given are the coefficients of the geometrical shapes fitted through the glenoid, humeral head, trochlea humeri and parts of the radius. r = radius; e = estimated error [Equation (3)]

Axes of rotation	P_x (cm)	P_y (cm)	P_z (cm)	e (cm)	V_x	V_y	V_z	e (deg)
GH rotation center	25.92	2.66	36.44	1.65				
Flexion/Extension axis	28.24	−0.26	4.79	1.27	−0.9935	−0.1027	−0.0574	1.45
Pro/Supination axis	30.29	2.53	−5.07	0.55	0.0989	0.2993	−0.9491	0.91
Geometric shapes	P_x (cm)	P_y (cm)	P_z (cm)	r (cm)	V_x	V_y	V_z	e (cm)
Glenoid (sphere)	26.16	2.63	36.77	2.91				0.03
Humeral head (sphere)	26.45	2.97	35.92	2.73				0.05
Elbow circumference (cylinder)	0.00	−1.62	2.94	1.33	0.9976	0.0432	0.0540	0.16
Radial circumference at Biceps Insertion (cylinder)	29.38	1.21	0.00	1.00	−0.1997	−0.2913	0.8983	0.07
Radial circumference at Supinator Insertion	29.52	1.09	0.00	0.69	−0.2875	−0.3738	0.8818	0.03
Radial circumference at Pronator Quadratus Origin	28.76	0.59	0.00	0.83	−0.2746	−0.3610	0.8912	0.21

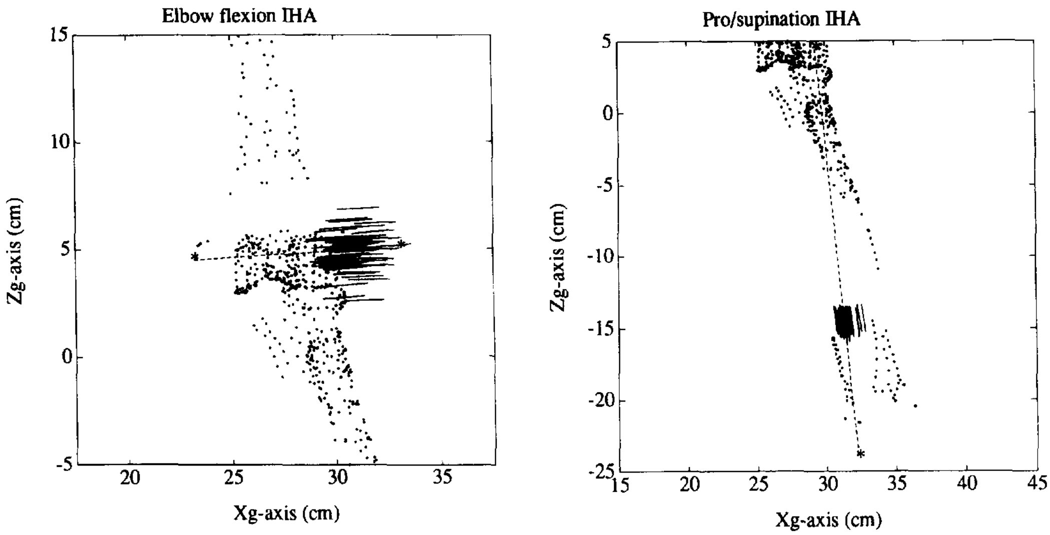

Fig. 2. Examples of the IHA calculations for elbow flexion–extension (A) and forearm pro-supination (B). The X_g–Z_g plane roughly corresponds with the frontal plane. IHA are drawn with a length of 2 cm. The optimal axes are plotted as dashed lines and have lengths of 10 cm for the flexion axis and 30 cm for the pronation axis.

Table 4. Muscle parameters for the selected arm muscles of specimen #4_r. Blank entries in the columns indicate that data were not available. PCSA = physiological cross-sectional area. When pennation angle was smaller than 15°, PCSA(1) and PCSA(2) have been estimated with $\alpha = 15°$. ρ = muscle density = 1060 kg/m^3 (Cutts and Seedhom, 1993)

Muscle	Muscle mass (g)	Muscle volume (ml)	Belly lengh (mm)	Pennation angle (°)	PCSA(1) $m/\rho l \cos(\alpha)$ (cm^2)	PCSA(2) $v/l \cos(\alpha)$ (cm^2)	PCSA(3) v/l (cm^2)
Biceps caput Breve	67	64	250	< 15	2.42	2.47	2.56
Biceps caput Longum	67	64	230	< 15	2.66	2.69	2.78
Coracobrachialis	43	42	200	< 15	1.96	2.03	2.10
Triceps caput Longum	152	142	300	30	4.14	4.10	4.73
Triceps caput Mediale		126	240	45		3.71	5.25
Triceps caput Laterale	117	111	290	30	3.30	3.32	3.83
Brachialis	128	122	220	< 15	5.30	5.36	5.55
Brachioradialis	69	66	230	< 15	2.71	2.77	2.87
Supinator	23	17		< 15			
Pronator Teres	35	33	200	< 15	1.60	1.59	1.65
Anconeus	10	11	85	30	0.96	1.07	1.24
Pronator Quadratus	12	12	42	< 15	2.60	2.76	2.86

The data obtained in this study allow for the implementation of upper extremity muscles and axes of rotation in a musculoskeletal model of the upper extremity. In addition, it was shown that the glenohumeral joint and elbow joint can be modeled as a ball-and-socket joint with three degrees of freedom and a double hinge joint with two degrees of freedom. The data obtained in this study may need to be scaled when used in combination with the data from other sources. How to scale the data from different sources is, however, still uncertain, and will be addressed in future work.

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