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INERTIA AND MUSCLE CONTRACTION PARAMETERS FOR MUSCULOSKELETAL MODELLING OF THE SHOULDER MECHANISM

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Abstract—To develop a musculoskeletal model of the shoulder mechanism, both shoulders of seven cadavers were measured to obtain a complete set of parameters. Using anthropometric measurements, the mass and rotational inertia of segments were estimated, followed by three-dimensional measurements of all morphological structures relevant for modelling, i.e. muscle origins and insertions, muscle bundle directions, ligament attachments and articular surfaces; all in relation to selected bony landmarks. Subsequently, muscle contraction parameters as muscle mass and physiological cross-sectional area were measured. The method of data collection and the results for inertia and muscle contraction parameters as prerequisites for modelling are described.

INTRODUCTION

Musculoskeletal models

The development of musculoskeletal models is one of the major topics in biomechanics. Musculoskeletal models are used to establish a relation between the motions of the bones and the muscle forces causing these motions (Fig. 1). The aim of these models is, on the one hand, to gain insight into the factors which affect the relation, e.g. position, of the rotation centre, muscle attachments, muscle characteristics, etc., and on the other hand, to determine which muscles are involved and what the joint reaction forces are. To describe the mechanical behaviour of a musculoskeletal system, many of its characteristics have to be considered. Due to the complexity of the system and depending on the purpose of the model involved, assumptions have to be made for most of these characteristics in order to develop an adequate and manageable model.

Firstly, bones are usually assumed to be rigid bodies. In the Newton–Euler approach the free body diagram and motion equations of this rigid body are derived. These equations include inertia properties, motion constraints and forces. To describe the dynamics of a musculoskeletal system, inertia properties of the system should be included. This means that segment mass, the segment centre of mass and the segment motions of inertia have to be implemented in the model.

Secondly, within a model the direction of muscle force depends on the assumed geometry of muscle attachments, while the magnitude depends on assumptions concerning contraction characteristics and stimulation. Usually, the direction of the force of a muscle will be modelled along one muscle line of action, in spite of occasionally large attachment sites and complex architecture. One can distinguish the centroid line approach in which the moment arm of a muscle depends on the curved line that is formed by the centroid of that muscle, and the straight line approach which connects origin and insertion of a muscle (Jensen and Davy, 1975). Thirdly, contraction characteristics for force magnitude development involve muscle architecture, bundle length, tendon length, muscle length, contraction velocity and physiological cross-sectional area (PCSA). In most cases only the PCSA is included in a musculoskeletal model to get an approximation of the maximal force which a muscle can exert. The magnitude of the force exerted by a ligament depends on non-linear elastic characteristics, while the force direction depends on the position of ligament attachments. The effect of soft tissue surrounding bones, joints and muscles, including the effect of the joint capsule, is usually neglected.

To develop a sound musculoskeletal model, parameters describing all of the characteristics mentioned above should be included. For consistency, these parameters should preferably be measured within one subject. Despite the availability of new techniques like magnetic resonance imaging (MRI), information on parameters is still highly dependent on cadaver studies. To date, no studies describing all of the information needed to derive the inertia, geometry and muscle contraction parameters have been published. In a musculoskeletal model, a relation between muscle force and calculated or prescribed motion is established. Thus, in order to validate the model, both motion and muscle force have to be known. In addition, to use such a model with a registration of gross motor actions like walking or riding a wheelchair, the position of the optical markers has to be known with respect to the geometry of the musculoskeletal system,

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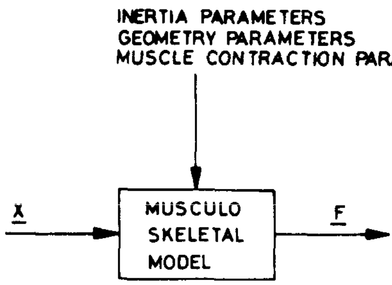

Fig. 1. Block diagram of a musculoskeletal model. x: vector of position, velocity and acceleration of the bones; E: vector of muscle forces.

in order to combine recorded motion with the accurate position of e.g. joint rotation centres and muscle attachments. To date the parameters of the musculoskeletal system and the motion pattern cannot yet be measured within one subject. Moreover, muscle force cannot be measured directly and is usually estimated with help of EMG. Therefore, musculoskeletal models can only be validated in a more qualitative sense.

The shoulder mechanism

The shoulder mechanism is an example of a very complex musculoskeletal system. The shoulder girdle consists of scapula and clavicle and functions as a movable but stable base for the motions of the humerus. The sternoclavicular (SC-) joint connects the clavicle and sternum, and the scapula in its turn is connected to the clavicle by the acromioclavicular (AC-) joint. Another connection between scapula and thorax is the scapulothoracic gliding plane, which constrains possible movements with two degrees of freedom and makes the system a closed chain. The humerus articulates with the scapula at the glenohumeral (GH-) joint, a ball-and-socket joint. Three extracapsular ligaments can be identified in the shoulder girdle: the costoclavicular ligament limiting the range of motion of the SC-joint, and conoid and trapezoid ligament acting at the AC-joint. Seventeen muscles are crossing the joints of the shoulder mechanism. Most muscles are polyarticular, fan-shaped and have large attachment sites.

For the movements of the humerus the large range of motion of the scapula over the thorax is essential. Since the motion of the scapula over the thorax is non-planar, it is very hazardous to measure or describe it as a planar motion without making mistakes due to distortion of the image or omitting the constraints of clavicle and thorax. It is, however, difficult to reconstruct the actual motion of the scapula, since it moves underneath the skin and is inaccessible for camera registration, except for X-rays, for which the complications are obvious.

Scapular motions are related to those of the humerus. For this reason the position of the scapula is standardized with respect to the humerus (Inman *et al.*, 1944; Pronk, 1988). Positioning the scapula is an active mechanism and consequently it is not self-evident that passive movements of the humerus result in the same scapulohumeral rhythm as active movements. Presently, knowledge about the shoulder mechanism as a whole is generally qualitative. Until now no three-dimensional musculoskeletal model of the shoulder mechanism has been published. To develop such a model, many parameters describing the inertia, geometry and muscle contraction characteristics of the system have to be known. Despite a number of studies on the shoulder girdle, each study has included only part of the parameters needed, and even if all studies are combined a large number of data will be missing.

Literature review

Formulae for the prediction of segment masses based on dissection and anthropometric data have been published by Barter (1957), Clauser *et al.* (1969) and Clarijs and Marfell-Jones (1986), while Clauser *et al.* also give predictions for the volumes and positions of the centres of gravity of the segments. Hinrichs (1985) determined predictions for moments of inertia based on the study of Chandler *et al.* (1975). During preparation of this manuscript new, non-linear prediction equations based on Chandler *et al.* (1975) were published by Yeadon and Morlock (1989).

The morphology and functional characteristics of the sternoclavicular joint were studied by Bearn (1967) and Depalma (1973). The orientation of joint surfaces of the acromioclavicular joint was described by Urist (1946) and Moseley (1972). The glenohumeral joint is the most extensively studied joint, probably due to its resemblance to a ball-and-socket joint. The orientation of the glenoid (Friedel, 1926; Freedman and Munro, 1966; Oxnard, 1967; Saha, 1971), and the radius of the glenoid and/or the humeral head (Dempster, 1955; Saha, 1961, 1971, 1973; Poppen and Walker, 1976, 1978; Hogfors *et al.*, 1987) are the most elaborated items. Braune and Fischer (1888) and Pfuhl (1934) have studied the function of the shoulder articulations, while Mollier (1899), Shiino (1913) and Hvorslev (1927) tried to simulate shoulder joint movements.

The length and thickness of both conoid and trapezoid ligaments have been investigated by Salter *et al.* (1987). Fukuda *et al.* (1986) measured the distance between coracoid process and clavicle and deducted the length of the coracoclavicular ligaments. Hogfors *et al.* (1987) have started to measure the position of the muscle attachments of the shoulder girdle three-dimensionally. Due to the limited description of their measurement method and data processing, it is not yet clear how their recorded data must be valued. Recently, Wood *et al.* (1989a,b) published results of a cadaver study, based on a centroid line approach. The length of some muscles have been measured (Mollier, 1899; Fick and Weber, 1877; Shiino, 1913; Hvorslev, 1927; Bassett, 1983), as well as bundle length (Shiino, 1913; Bassett, 1983; Howell *et al.*, 1986), centroids (Bassett, 1983) and moment arms (Bassett, 1983; Howell *et al.*, 1986). The physiological cross-sectional area (PCSA) of shoulder muscles was measured directly by Fick (1911), Shiino (1913) and Poppen and Walker (1978). The PCSA has been calculated from the product of muscle mass and inverse density divided by bundle length (Weber, 1851; Fick, 1911), the quotient of volume and muscle length (Bassett, 1983; Wood *et al.*, 1989a), the muscle volume and bundle length (Bassett, 1983; Howell *et al.*, 1986) and maximum cross-sectional area perpendicular to the centroid (Wood *et al.*, 1989a).

Motion studies of the shoulder joint have often been limited to the glenohumeral joint (Poppen and Walker, 1978; Engin and Peindl, 1987; Peindl and Engin, 1987). Registration of the motion of the shoulder girdle has been performed using two-dimensional X-ray photographical studies (Inman *et al.*, 1944; Saha, 1961; Meijers, 1961; Freedman and Munro, 1966; Poppen and Walker, 1976; Dvir and Berme, 1978), cinematographical studies (Engen and Spencer, 1968; Hvorslev, 1927), goniometers (Conway, 1961; Doody *et al.*, 1970a,b), or pins inserted into the clavicle and scapula (Inman *et al.*, 1944; Inman and Saunders, 1946; Kennedy and Cameron, 1954). All of these studies recorded only part of the essential three-dimensional movement of clavicle, scapula and humerus. Only a few authors (Wallace, 1982; Wallace and Johnson, 1982; Peterson *et al.*, 1985) report the result of three-dimensional X-ray recordings of the motions of the shoulder girdle. They did not, however, present a three-dimensional motion description. Recently in our research group, attempts have been made for a three-dimensional recording with use of a new instrument, the so-called palpator (Pronk, 1988).

Towards a musculoskeletal model of the shoulder mechanism

Our goal is to develop a three-dimensional musculoskeletal model of the shoulder mechanism. Such a model. will improve the understanding of complex behaviour of this mechanism, so that it will be useful in clinical practice. Classic Newton–Euler and Lagrangian approaches involve a large number of equations and derivations. In addition, the complex motion constraint of the scapulothoracic gliding plane will limit the application of these approaches. Therefore a kinematical and dynamical finite element method is used to develop a three-dimensional musculoskeletal model (Pronk, 1988, 1989; Van Der Helm, 1988; Van Der Helm and Pronk, 1989).

The predictive values of this musculoskeletal model will heavily depend on the parameters describing the characteristics of the system. It would be preferable that a whole set of parameters is derived from one subject, since the interaction between certain parameters is not yet understood. Therefore, an extensive morphological study is performed in order to acquire a complete set of parameters for the shoulder mechanism. To date, the only way to derive these parameters is by a dissection experiment. In this paper the results are reported of a study of seven cadavers. For each cadaver, the inertia parameters, segment mass and centre of gravity, were estimated from anthropometric data using the regression equations of Clauser *et al.* (1969), and the three-dimensional coordinates of morphological structures were measured. Obviously, muscle contraction parameters as force–length and force–velocity relations were impossible to derive from these dissection experiments. The only parameter which could reasonably be derived was the maximal force output of a muscle. Therefore, for each muscle in the shoulder mechanism, the PCSA and muscle mass were measured.

MATERIALS AND METHODS

Seven preserved human bodies (five males and two females) were used. No pre-experimental selection of cadavers on age at death or physical appearance took place.

During the experiment the following sequence of steps was made:

(1) measurement of relevant body dimensions for the derivation of inertia parameters segment mass, volume, segment mass position and moments of inertia;

(2) measurement of well-palpable bony landmarks for future comparison with *in vivo* measurements;

(3) to enable reconstruction after dissection of the original positions of humerus, scapula, clavicle and thorax in a global, whole-body, coordinate system, small screws were placed in the four different 'segments' so as to define the separate local coordinate systems;

(4) measurement of the positions of the screws on the four segments with respect to a global, Cartesian coordinate system;

(5) dissection and exarticulation of the cadavers at the scapulothoracic, acromioclavicular, sternoclavicular and glenohumeral joints. During the process, muscles were cleaned and cut, and fibre bundles were marked with coloured beads for future identification;

(6) measurement of the locations of muscle and ligament insertions and relevant articular surface shapes on the exarticulated segments relative to the screws;

(7) the muscle parameters mass and cross-sectional area were determined.

Determination of inertia parameters

On all cadavers the body dimensions necessary for the calculation of inertia parameters from regression equations as published by Clauser *et al.* (1969) and Hinrichs (1985) were measured. Measurements were made on the left-hand side of the body, following the protocol and definitions of Clauser *et al.* as much as

Table 1. Structures measured on scapula, humerus, thorax and clavicle of all cadavers. The additions '–O' and '–I' stand for origin and insertion

Scapula	Humerus	Reference markers Thorax	Clavicula
Reference marker 1	Reference marker 1	Reference marker 1	Reference marker 1
Reference marker 2	Reference marker 2	Reference marker 2	Reference marker 2
Reference marker 3	Reference marker 3	Reference marker 3	Reference marker 3
Reference marker 4	Reference marker 4	Reference marker 4	Reference marker 4
Reference marker 5	Reference marker 5	Reference marker 5	Reference marker 5
Reference marker 6	Reference marker 6	Reference marker 6	Reference marker 6
Muscles			
Deltoideus-O	Deltoideus-I		Deltoideus-O
Subscapularis-O	Subscapularis-I		
Supraspinatus-O	Supraspinatus-I		
Infraspinatus-O	Infraspinatus-I		
Teres minor-O	Teres minor-I		
Teres major-O	Teres major-I		
Biceps cap.brevis-O	Biceps-I*		
Biceps cap.longum-O			
Coracobrachialis-O	Coracobrachialis-I		
Triceps cap.longum-O	Triceps-I*		
Latissimus dorsi-O	Latissimus dorsi-I	Latissimus dorsi-O	
Trapezius-I		Trapezius-O	Trapezius-I
Rhomboideus-I		Rhomboideus-O	
Levator scapulae-I		Levator scapulae-O	
	Pectoralis major-I	Pectoralis major-O	Pectoralis major-O
Pectoralis minor-I		Pectoralis minor-O	
Serratus anterior-I		Serratus anterior-O	
Ligaments			
Lig. conoideum			Lig. conoideum
Lig. trapezoideum			Lig. trapezoideum
		Lig. costoclavicularis	Lig. costoclavularis
Articular surfaces			
Art. surface glenohum.	Art. surface glenohum.	Art. surface Costoclav.	Art. surface Costoclav.
Art. surface Acromioclav.			Art. surface Acromioclav.
Art. surface Coracoclav.			Art. surface Coracoclav.
		Art. surface sternoclav.	Art. surface sternoclav.
Anatomical landmarks			
Trigonum spinae	Epicondylus medialis	Scapulothoracic wall	
Angulus inferior	Epicondylus lateralis	Incisura jugularis	
Angulus acromialis	Olecranon	C7	
Art. Acromioclav. (l.m.)			
	Tuberculum minus		
	Tuberculum majus		
	Collum humeri	Muscle path serratus ant.	
	Sulcus humeri		

*Measured on the forearm.

possible. Table 2 sums up the dimensions measured on all cadavers. Chandler *et al.* (1975) presented inertia tensors about anatomical axes of segments which had been determined for each segment using the pendulum technique. From this, the direction of the principal axes around which the matrix becomes diagonal and the related principal moments of inertia could be calculated. Hinrichs (1985) and Yeadon and Morlock (1989) reduced data for limb segments further by averaging the anterior–posterior and medial–lateral moments of inertia, and subsequently determined regression equations for one mean transversal moment of inertia and longitudinal moment of inertia. The total inertia tensor could thus be reduced to two moments of inertia about a transverse axis and the longitudinal principal axis of a segment through its centre of mass. An illustration of procedures for obtaining segment data has been given by Kaleps *et al.* (1984).

Centres of mass have generally been estimated relative to proximal landmarks (Clauser *et al.*, 1969). Moments of inertia have been given as predictions

Table 2. Summary of the population characteristics of this and other relevant studies

		(N)	Age (yr)	s.d.	Stature (cm)	s.d.	Weight (kg)	s.d.	Embalmed
Bischoff	(1863)	1	33	—	168.0	—	69.7	—	—
Theile	(1884)	1	26	—	166.7	—	64.0	—	—
		2	64.5	19.1	—	—	33.9	4.5	—
Dempster	(1955)	8	68.5*	11.0	169.4	11.2	59.8	8.3	1
Clauser *et al.*	(1969)	13	49.3	13.7	172.7	13.7	66.5	8.7	13
Bassett	(1983)	4	66.3	9.9	—	—	—	—	—
Clarijs and Marfell-Jones	(1986)	6	66.8	25.7	—	—	57.6	13.4	—
Hogfors *et al.*	(1987)	3	55–71	—	—	—	—	—	?
Wood *et al.*	(1989)	1	—	—	183.0	—	90.70	—	1
This study		7	80.0	7.0	171.1	6.9	76.1	16.4	7

*$N=6$.

following Hinrichs (1985) about the principal axes through the centres of mass based on the study by Chandler *et al.* (1975). Original definitions of landmarks are given in McConville *et al.* (1980).

Determination of geometry parameters; identification of coordinate systems

For each cadaver a global coordinate system (Fig. 2) was defined as related to the anatomical conventions as a system with its:

—origin in the incisura jugularis;

—X-axis along the frontal plane towards the right shoulder;

—Y-axis directed cranially; and

—Z-axis in the sagittal plane towards the back.

Configuration measurements needed to determine the position of the segments with respect to the global system took place prior to dissection. For measurements, a metal frame was constructed in which the cadaver could be fixed (Fig. 3). After the legs were removed, the upper half of a cadaver was positioned into the frame via a rod through the head in such a way that the frontal plane was as much as possible parallel to the frontal face of the frame. Movement in both the frontal and lateral directions was prevented by fixation of the pelvis. The elbows of the cadaver were extended maximally and the arms were tied to the torso. Since the influence of gravity during the measurements might affect the accuracy of results, sagging was checked for one cadaver. Over a period of 2 h (twice the measurement period), no change in the position of reference markers could be measured. The faces of the frame were used as the reference planes of an orthogonal coordinate system. Three-dimensional positions of morphological structures were measured with use of a 'palpator' (Fig. 4). The palpator is an open chain of four links of 0.2 m each, connected by four perpendicular hinges. The rotation of each hinge is recorded with a potentiometer and is on-line A–D converted (Olivetti M21, DT2801 AD converter). The three-dimensional position of the end-point of the fourth link can be calculated with respect to an internal co-ordination system of the palpator, defined previously in calibration measurements. Using the palpator, a large number of datapoints can be collected in a fast and easy way. The measurement error of the palpator was estimated to have a standard deviation of 0.96 mm per coordinate or 1.43 mm in absolute distance (Pronk and Van Der Helm, 1991).

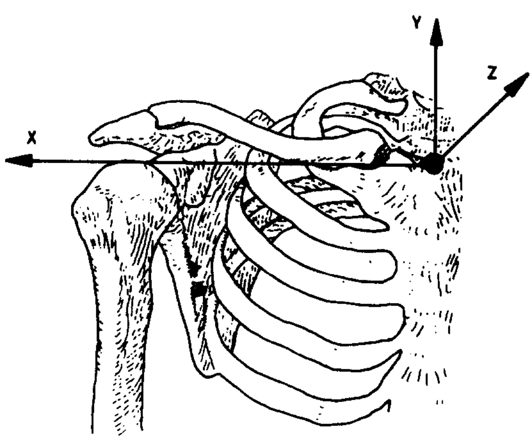

Fig. 2. Ventral view of a right shoulder mechanism with its global coordinate system. Shown are thorax, scapula, clavicle and humerus. Origin: incisura jugularis, x-axis: left to right; y-axis: caudal to cranial; z-axis: ventral to dorsal.

Due to the impossibility of reaching all structures within the same coordinate system without damaging the interrelations, and the restricted reach of the palpator, measurements of the four segments within their own coordinate systems were needed. To reconstruct the data of the segment measurements in the global coordinate system and thus to allow descriptions of segments relative to each other within a whole-body setting, at least four non-collinear joint reference markers (which are measured in both the global and the separate segment systems) were required. For reference markers, six Pozidriv screws (2.5 × 12 mm) were inserted into the bone of each segment: humerus, clavicle, scapula and thorax.

Using conjoined markers and regarding the segments as rigid bodies, the rotation matrix and translation vector for transformation of data from the individual segment system measurements to the global (whole-body) configuration could be calculated according to Veldpaus *et al.* (1988)

For each side of a cadaver, reference markers were measured five times, thus forming the database needed for transformation towards the global system. For future calculations, the data from the left-hand side of the body were transformed to the right-hand side.

In addition to the measurements described, a selection of selected anatomical landmarks were measured for future connection of these landmarks with subcutaneous dimensions. These landmarks are listed in Table 1.

Summing up, two subsequent transformations will be required after data collection:

(1) transformation of data measured on insertions and shapes of articular surfaces from individual segment coordinates to the global coordinate system using the configuration of reference markers to estimate rotation matrix R and translation vector $\mathbf{v}$;

(2) transformation of data measured on the left-hand side of the body to the right-hand side, thus creating a set of descriptions of 14 shoulder mechanisms, all within coordinate systems comparable by their definitions with respect to the global coordinate system.

Determination of geometry parameters; exarticulation and data collection

Following the global measurements, cadavers were partly dissected by students as part of their dissection course under supervision of the authors. Dissection consisted of identification and cleaning of shoulder muscles and their attachments. Before removal by standardized cuts, some representative muscle fibre bundles were marked with coloured beads which were fastened close to the attachments of these bundles. Thus, after exarticulation, the direction of muscle fibre bundles could be reconstructed by connecting the coordinates of beads of the same colour. Exarticulation was performed by the authors at the glenohumeral, sternoclavicular and acromioclavicular joints, and the scapulothoracic wall, with as little damage to ligaments, attachments and articular surfaces as possible.

Local system measurements took place using the same frame as for the configuration measurements. Segments were positioned and fixed so that all data points could be measured without changing the position of either the segment measured or the base of the palpator. The humerus was fastened with the elbow extended.

For each muscular or ligamentous attachment or articular surface a large number of datapoints was collected. Table 1 is a listing of structures measured. The position of these structures will subsequently be described by fitting data to a geometrical form. Dependent on the fitting procedure for each structure, sufficient data had to be collected, ranging from 3 to 5 points (for instance the origin of m. coracobrachialis), up to 30–50 points for a structure needing a more complex fitting procedure (e.g. the surface of the glenohumeral joint).

Fitting procedures used in this project will be estimations of the parameters of a point, line, plane, ellipsoid, cylinder or a sphere. The algorithms for these fittings are described extensively elsewhere (Van Der Helm *et al.*, 1991).

Determination of muscle contraction parameters

Information on muscle bundle direction was collected by measuring coordinates of the fixations of muscle bundles that were earlier marked with beads.

Following the measurement of attachment locations and articular surfaces, all muscles listed in Table 1 were removed from their bony fixtures for weighing. To ensure comparable measurements for all cadavers at equal levels of saturation, muscles were kept in a solution of formalin and weighed three times at intervals of approximately one week. Based on the recordings of muscles that were observed not to be completely saturated, results for each muscle recording less than 96% of the mean weight of that muscle with a minimum difference of 2.5 g were discarded on the assumption of incomplete saturation.

Physiological cross-sectional areas (PCSA) were determined using the following procedure: out of all muscles, thin coupes are cut at the level of the apparently largest cross-sectional area perpendicular to the bundle direction of the muscle. The coupes coming from flat muscles (e.g. m. serratus anterior) are rolled up and together with coupes of more easily measurable muscles (e.g. m. biceps brachii) photographed for area determination using a digitizer (Summagrahics Supergrid, accuracy 1/40 mm). All PCSA coupes were digitized within an accuracy of $10\ \text{mm}^2$.

Lastly all humeri, clavicles and scapulae were cleaned and stored for future reference.

RESULTS

The population of this study was selected on availability. Moreover, as a consequence of the duration of the dissection project, embalmed cadavers were used. Table 2 gives the population characteristics, combined with available data on other relevant cadaver studies. In relation to these studies, this population was considerably older ($\bar{x} = 80.0$) and heavier ($\bar{x} = 76.13$) than other cadaver populations. Mean stature, however, equals the population used by Clauser *et al.* (1969). Cadaver studies specifically focusing on the shoulder have usually been performed on a half- or quarter-specimen (Shiino, 1913; Poppen and Walker, 1978; Basset, 1983; Howell *et al.*, 1986) and general anthropometric data describing the individual bodies are missing. A comparison with those studies was thus not possible.

Determination of inertia parameters

The results for the anthropometric measurements are summarized in Table 3. The cadaver population

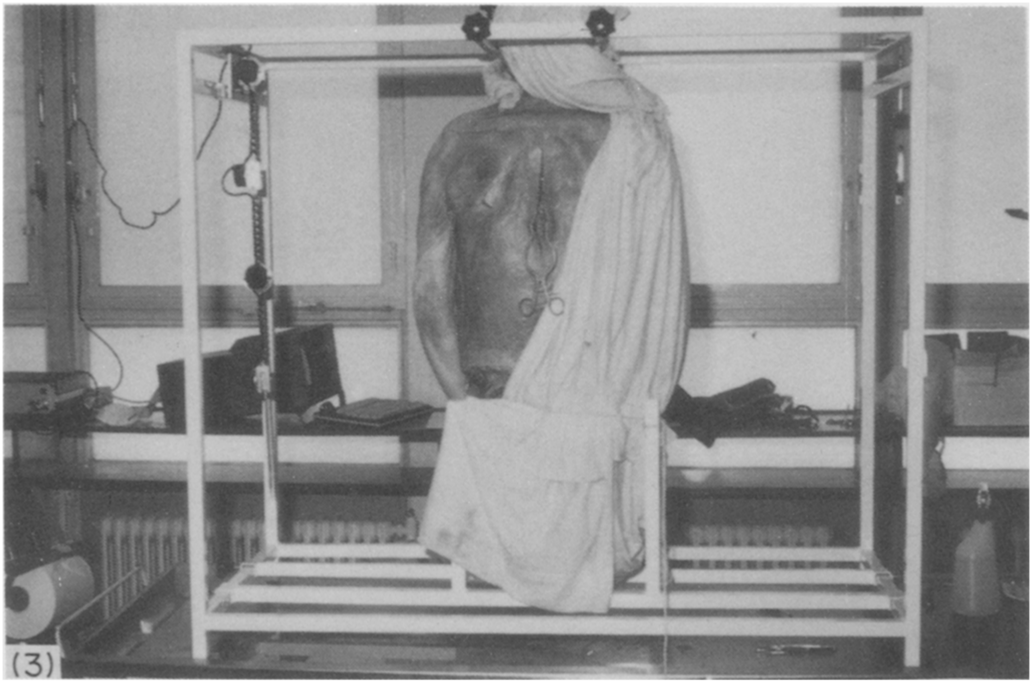

Fig. 3. Fixation frame for cadaver measurements. The cadaver is seen from the back with the palpator fixed to the frame on its left-hand side.

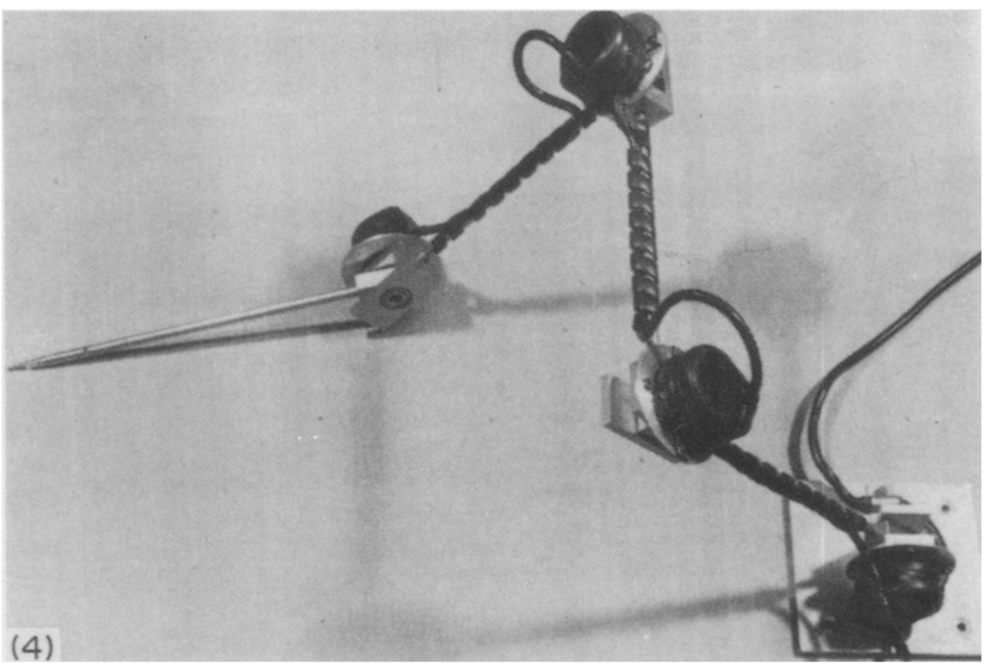

Fig. 4. The palpator: a measurement device to record three-dimensional coordinates.

Table 3. Results for a selection of anthropometric measurements required for the calculation of inertia parameters. Measuring procedures and descriptions were according to Clauser *et al* (1969). All values except weight (kg) are given in cm

	K1	K2	K3	K4	K5	K6	K7	Mean	s.d.
Gender	Male	Male	Male	Female	Female	Male	Male		
Age	76	90	70	86	82	82	74	80.00	7.02
Weight	104	72.9	69.2	71.3	88.9	74.9	51.7	76.13	16.43
Stature	181.6	172.7	179.4	164.2	166.1	167.6	166.5	171.16	6.92
Top of head to chin/neck intersect	24.7	23.6	22.2	22.8	21.9	24.3	21.5	23.00	1.23
Top of head to trochanterion	85.8	85.5	83.9	79.8	86.7	81.8	83.5	83.86	2.43
Top of head to tibiale length	48.4	45.2	51.2	47.7	45.3	44.8	43.7	46.61	2.61
Chest depth	27.1	19.7	24.3	25.3	23.6	22.1	20.1	23.17	2.71
Bicristal breadth	34.7	32.2	27.3	34	36.8	34.3	29.5	32.69	3.28
Bispinous breadth	24.4	26.5	23.7	25.1	29.6	27.4	24	25.81	2.14
Elbow breadth	8.33	6.87	7.50	5.93	6.63	6.98	7.03	7.04	0.74
Hand breadth	8.77	8.40	8.27	7.63	7.23	8.46	8.00	8.11	0.53
Wrist breadth	6.40	5.73	6.00	5.47	5.40	5.72	5.90	5.80	0.34
Head circumference	62.6	59.0	58.8	58.4	60.2	60.0	60.5	59.93	1.42
Chest circumference	120.3	101.7	99.8	104.0	110.7	100.0	89.5	103.72	9.7
Waist circumference	115.5	91.3	83.7	103.0	113.2	102.0	79.0	98.24	14.07
Axillary arm circumference	36.1	28.0	29.3	32.6	32.8	27.7	23.0	29.93	4.30
Biceps circumference	31.1	24.7	26.6	31.3	30.9	25.6	21.3	27.36	3.87
Forearm circumference	29.0	23.9	25.1	25.3	26.0	24.9	22.3	25.23	2.05
Wrist circumference	19.5	17.9	18.1	17.2	17.7	18.4	17.5	18.06	0.76
Acromion–radiale length	35.1	34.7	35.5	31.0	29.7	31.9	29.8	32.55	2.52
Ball of humerus–radiale length	33.8	34.5	35.2	30.6	31.1	31.1	28.8	32.16	2.35
Radiale–stylion length	28.1	27.0	27.7	24.6	22.3	24.3	26.2	25.74	2.08
Fat iliac crest	18.0	11.7	7.9	12.5	23.0	18.0	7.3	14.06	5.81

was very heterogeneous: cadaver 7 was half as heavy as cadaver 1 (51.7 vs 104 kg), while for instance waist circumference varied from 79 to 115.5 cm. The anthropometric data were used for the estimation of segment properties on basis of regression equations published by Clauser *et al.* (1969). For definition of segmentations, the reader should refer to Clauser *et al.* (1969). The longitudinal and transversal principal moments of inertia were predicted relative to the centre of mass of the segments (Hinrichs, 1985). Values are given in Table 4. For one specimen (K7), estimated longitudinal moments of inertia of the upper arm and forearm were negative.

Determination of geometry parameters

To calculate the position of datapoints measured in the global coordinate system, a transformation function was estimated using a least-squares criterion (Veldpaus *et al.*, 1988). This transformation function describes the rotation and translation of the configuration of screws in a local coordinate system to the configuration in a global coordinate system. Normally six screws are used to estimate the transformation function. However, in some cases, the screws were irretrievable or malpositioned and could thus not be digitized. The mean and standard deviation of the mean residual error associated with estimations of the transformation function are shown in Table 5.

Determination of muscle contraction parameters

Results of PCSA measurements and muscle masses, combined with relevant data from other authors, are given in Tables 6 and 7. In this study of m. triceps, only the long head was measured. For those authors who gave data for the separate parts of m. deltoideus (Shiino, 1913; Poppen and Walker, 1978; Howell *et al.*, 1986; Wood *et al.*, 1989a), the combined figure is given. Data from Wood *et al.* (1989a) on PCSA listed in Table 7 are values calculated on basis of Coons surface grid data. Also included are their cross-sectional data calculated from volume and muscle length.

Statistical comparison on the existence of left–right differences for PCSA or muscle mass within each body (t-test, 16 or 17 muscles, $p<0.01$) did not lead to significant results. Between PCSA and muscle mass a strong correlation was found; all muscles except m. levator scapulae, m. trapezius, m. infraspinatus and m. supraspinatus showed a significant correlation (Pearson correlation; $N=14$, $p<0.01$).

DISCUSSION

Descriptions of data on inertia parameters, geometry parameters and muscle contraction parameters (PCSA and mass) of the shoulder mechanism muscles have not often been reported on. This is not surprising since the importance of such data, besides being merely descriptive, has largely been dependent on the application of such data in a musculoskeletal model. Since the physical models of the 19th and early 20th century (Mollier, 1899; Shiino, 1913; Hvorslev, 1927) and the until now essentially two-dimensional models of Poppen and Walker (1978) and Howell *et al.* (1986), progressing computerization has facilitated development of a three-dimensional model of the shoulder mechanism and has thus increased the need for a complete set of data.

The cadavers used in this study were generally older, taller and heavier than in other cadaver studies (Table 2), although the difference in average stature

Table 4. Inertia parameters segment mass, segment mass position and segment volume, calculated on basis of regression equations by Clauser *et al.* (1969) and transversal and longitudinal moments of inertia, calculated on basis of equations by Hinrichs (1985). Given in brackets are the positions relative to which segment mass positions are given. Original definitions of landmarks are given in McConville *et al.* (1980). IJ = incisura jugularis, AC = acromion, CR = caput radii, MCIII = distal head of third metacarpal

	K1	K2	K3	K4	K5	K6	K7	Mean	s.d.
Segment masses (kg)									
head	5.88	5.04	4.96	4.95	5.41	5.17	4.88	5.19	0.35
trunk	54.23	39.46	37.66	37.35	48.33	37.90	29.30	40.60	8.17
head and trunk	60.76	43.16	42.94	41.98	53.92	42.81	32.95	45.50	9.07
total arm	4.55	3.29	3.43	3.68	4.00	3.49	2.64	3.58	0.60
upper arm	2.71	1.72	1.86	1.95	2.02	1.56	0.87	1.81	0.55
forearm	1.44	1.04	1.12	1.06	1.14	1.14	0.93	1.12	0.16
forearm and hand	2.01	1.56	1.67	1.45	1.44	1.55	1.41	1.58	0.21
hand	0.57	0.46	0.49	0.40	0.40	0.48	0.45	0.46	0.06
Segment mass positions (cm from proximal landmark)									
head (top of head)	12.6	11.6	11.3	11.3	11.6	11.9	11.6	11.7	0.5
trunk (IJ)	22.3	23.8	22.6	22.2	25.0	23.1	22.9	23.1	1.0
head and trunk (IJ)	58.5	53.4	54.1	54.6	53.0	55.0	50.5	54.2	2.4
total arm (AC)	33.7	34.3	35.5	29.2	30.2	32.1	30.2	32.2	2.4
upper arm (AC)	20.2	18.2	19.9	13.2	15.3	17.4	17.9	17.4	2.5
forearm (CR)	11.6	10.6	11.1	9.3	8.3	9.4	10.4	10.1	1.1
forearm and hand (CR)	17.7	17.7	18.1	15.4	13.7	15.7	18.0	16.6	1.7
hand (MCIII)	4.6	4.2	4.4	4.2	4.2	4.2	4.4	4.3	0.1
Segment volumes (1)									
head	5.6	4.8	4.7	4.7	5.1	4.9	4.7	4.9	0.4
trunk	53.2	36.6	34.6	35.7	45.1	37.7	25.3	38.3	8.8
head and trunk	59.4	44.3	42.6	42.8	53.3	42.0	34.0	45.5	8.3
total arm	4.3	3.0	3.2	3.4	3.7	3.2	2.4	3.3	0.6
upper arm	2.7	1.6	1.8	1.9	2.0	1.5	0.7	1.7	0.6
forearm	1.3	0.9	1.0	1.0	1.0	1.0	0.8	1.0	0.2
forearm and hand	1.8	1.4	1.5	1.3	1.3	1.4	1.3	1.4	0.2
hand	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.1
Transversal moments of inertia (kg cm^{-2})									
head	309.1	222.3	217.5	207.9	251.3	246.4	258.5	244.7	34.1
trunk	19,743.6	12,984.1	10,542.0	13,058.5	21,665.5	13,109.6	9331.5	14,347.8	4607.4
upper arm	161.8	143.2	156.5	110.2	92.8	109.2	73.7	121.1	33.4
forearm	108.9	82.4	91.0	49.7	31.7	59.3	70.2	70.5	26.1
hand	7.2	6.2	5.8	4.1	3.0	6.3	5.1	5.4	1.5
Longitudinal moments of inertia (kg cm^{-2})									
head	309.1	222.3	217.5	207.9	251.3	246.4	258.5	244.7	34.1
trunk	10,524.5	5524.5	3954.3	7941.8	10,049.3	7735.2	2983.2	6959.0	2907.6
upper arm	27.0	13.2	18.0	21.8	19.1	11.2	−0.7*	15.7	8.9
forearm	12.3	2.6	5.2	2.7	1.8	1.8	−1.0*	3.6	4.2
hand	2.3	1.8	1.6	0.8	0.2	1.9	1.3	1.4	0.7

*Estimation inaccuracy (see Discussion).

with Clauser *et al.* (1969) is small. The average difference in weight with the Clauser population seems mainly to be the result of a higher percentage body fat: the difference in waist circumference between both populations is 22% while the thickness of the panniculus adiposus on the iliac crest differed 33% (14.1 vs 10.6 mm).

The population in this study was heterogeneous. A pre-selection of cadavers on, for instance, weight or stature might have lowered the variance in anthropometrical results. This would however not necessarily have led to a lower variance in (muscle parameter) data concerning the shoulder.

Unfortunately, no information was available on shoulder complaints or shoulder malfunctioning during life, and thus the possibility exists that modelling will be performed using data derived from one or more malfunctioning shoulders.

Determination of inertia parameters

Within the aims and methods of this study, direct measurements of inertia parameters were not feasible. Fortunately, regression equations on the relation of anthropometric variables to inertia parameters have been published (Barter, 1957; Clauser *et al.*, 1969; Hinrichs, 1985; Clarijs and Marfell-Jones, 1986). Indirect determination of these parameters from anthropometric dimensions was thus tenable (Tables 3 and 4). For the interpretation of the accuracy of these derived segment property data, two factors should however be kept in mind. Firstly, the cadaver population of Chandler *et al.* (1975) on the basis of which

Table 5. Mean and standard deviation (in mm) of the residual errors e_t, e_c, e_s and e_h, associated with the estimation of the transformation from segment measurements to configuration measurements of thorax, clavicle, scapula and humerus. In most cases the mean residual error is averaged over the residues of six screws. Different numbers are indicated in brackets

		$\bar{e}_t$	$\bar{e}_c$	$\bar{e}_s$	$\bar{e}_h$
K1	right	1.10	0.70	2.13 (5)	2.04
	left	1.23	0.46 (5)	2.22	2.02 (5)
K2	right	0.86	1.74 (5)	2.56 (5)	2.55
	left	1.05	1.49	2.30	1.73
K3	right	1.33	1.64	1.78 (5)	1.96
	left	1.67	0.77	1.70	1.41 (5)
K4	right	0.87	1.25 (5)	2.32	2.04 (5)
	left	0.90	1.12 (4)	1.94 (4)	1.42
K5	right	1.19	0.93 (5)	1.34	2.02 (5)
	left	1.23	0.56 (5)	2.79 (7)	2.85
K6	right	0.84	2.14 (5)	2.37	2.68 (5)
	left	1.13	1.28	1.58 (5)	2.42 (5)
K7	right	1.15	0.83 (5)	2.56 (5)	2.18
	left	0.82	1.97	2.79 (5)	2.20
	Mean	1.09	1.21	2.17	2.11
	s.d.	0.24	0.53	0.45	0.42

Hinrichs (1985) calculated the inertia regression equations was small ($N=6$). Secondly, the difference between anthropometric dimensions of individual cadavers in this study and the Clauser and Chandler populations should be kept in mind, since predictions on the basis of multiple regressions will become inaccurate when calculated over data diverging too much from the original data set. The negative longitudinal moments of inertia calculated for K7 are thus probably the result of prediction inaccuracy due to the application of the formulae on diverging data. K7 was a light specimen with a body weight of only 51.7 g. Hinrichs (1985) describes a comparable estimation error. It is possible that non-linear regression equations given by Yeadon and Marlock (1989) might have led to better results. However, since measurements had taken place before publication of their results, not all anthropometric parameters needed were available (Table 4) and equations have not been used.

Since on all but one cadaver the skin on the legs was partially loosened, but not removed when the anthropometry was performed, for these cadavers, no leg anthropometry data could be collected. Hence, no comparison could be made between the sum of the segment masses and total body weight as in Miller and Morrison's (1975) study on the applicability of the regression equations on living subjects. For K2 this indirect control method of the comparison of total mass of all segments with body weight led to an overestimation of only 1.9%. It should, however, be kept in mind that the anthropometric dimensions of this cadaver fell well inside the range of anthropometric dimensions of the Clauser population. The moments of inertia estimated here were principal moments of inertia or the inertia tensor belong to a set of orthogonal axes in which only the diagonal values are non-zero. These principal axes have their origin in the centre of mass, and the longitudinal principal axis is approximately aligned with the longitudinal axis of the segment as defined by the bony landmarks (Chandler *et al.*, 1975; McConville *et al.*, 1980; Kaleps *et al.*, 1984). In most limb segments excellent alignment between the principal axes and the anatomical axes can be achieved by a minor rotation over a single axis (McConville *et al.*, 1980).

Determination of muscle contraction parameters

The PCSA of a muscle is used as an indication of its maximal strength. The relation between force and area for human subjects has been calculated by several authors. On basis of analyses of data from earlier studies and their own results, Weijs and Hillen (1985) determined this relation for human jaw muscles as $P=0.33\times10^6\,\mathrm{Nm}^{-2}$. This value includes, however, the uncertainty of the effect of muscles possibly being measured at different lengths as the result of differences in body posture at embalming, thus representing different positions in the force–length diagram.

Apart from data published by Weber (1851), no complete set of PCSA of shoulder mechanism muscles has come to the knowledge of these authors. Between data from this study and earlier publications, some striking differences in PCSA can be noted (Table 6). It should, however, be kept in mind that Weber measured on a young, muscular cadaver and Shiino (1913) selected three muscular specimens out of a total of 30 for the calculation of his average results. Moreover, Weber's (1851) measurements return in Fick's (1911) and Poppen and Walker's (1978) data. Also, different determination methods have been used: calculation of the PCSA from muscle mass and length (Weber, 1851); calculation on basis of volume and muscle length (Bassett, 1983; Wood *et al.*, 1989a), volume and bundle length (Bassett, 1983; Howell *et al.*, 1986) or on basis of

Table 6. Physiological cross-sections of shoulder muscles (in cm^2) of this study compared with other results

	Physiological cross-sections (cm^{-2})									
	Weber (1851)	Fick (1911)	Shiino (1913)	Poppen and Walker (1978)	Bassett (1983)	Howell *et al.* (1986)	Wood *et al.* (1989)	Wood *et al.* (1989)	This study	
No. of shoulder specimen		($N=6$)	($N=3$)	($N=2$)*	($N=2\times2+1$)	($N=5$)	($N=1$)‖	($N=1$)¶	($N=7\times2$)	s.d.
Biceps cap. med.	9.15	6.55	5.90		2.04		3.2	1.3	3.08	1.01
Biceps cap. lat.			5.10		2.16		7.1	1.9	3.21	1.07
Triceps	15.98†	4.75	15.00†		11.93		7.1†	3.8†	6.84†	1.58
Coracobrachialis	5.79	5.79§	5.50				1.3	1.2	2.51	0.91
Levator scapulae	2.58								2.82	0.50
Rhomboideus	6.52						12.3	12.9	6.27	1.94
Lat. dorsi	9.43		8.20	7.39	12.33		12.9	5.8	8.64	3.05
Trapezius	12.68						27.7	2.6	15.99	3.35
Teres major	9.81	9.81§	10.50		8.49		8.4	5.8	10.02	4.29
Teres minor	‡				‡		2.6	2.5	2.92	1.01
Infraspinatus	16.47‡	16.47§	13.20	11.36	13.59‡	17.57	8.4	5.8	9.51	2.97
Supraspinatus	7.71	7.71§	9.30	6.21	5.74	9.52	5.2	4.5	5.21	1.76
Subscapularis	25.24	25.24§	21.00	13.85	15.89	16.00	13.6	9.7	13.51	3.49
Deltoideus	25.31	25.30§	34.00	37.69	23.13	26.72	29.0	21.9	25.90	4.28
Pect. major	17.36		12.90		13.61		18.7	13.5	13.65	3.00
Pect. minor	4.18						4.5	3.8	3.74	0.99
Serratus anterior	12.80						13.6	13.0	13.93	3.46
Total	181.00						175.5	132.3	147.57	

*Two specimens combined with Fick's data.
†Long head only.
‡Infraspinatus + teres minor.
§Data from Weber.
¶Calculated with the use of Coons surface grids.
‖Calculated as volume/muscle length.

Table 7. Muscle weights (in g) as measured in this study compared with other results

	Muscle weights (g)								
	Weber (1851)	Bischoff (1863)	Theile (1884)			Shiino (1913)	Wood *et al.* (1989)	This study	
	($N=1$)	K.L.	T.III	T.XL	T.XLI	($N=2$)	($N=1$)	($N=7$)	
Age	—	33	26	78	51	—	—	80.0	7.0
Body weight	—	69.7	64.0	37.0	30.7	—	90.7	76.1	16.4
	Average	Left	Left	Left	(Left?)	Left	(Right?)	Average	s.d.
Biceps	124.6	177.5	181.7	55.9	40.0	80.0		114.1	32.1
Triceps	130.9*	122.0	423.1	161.9	92.2	98.0*		97.4*	18.2
Coracobrachialis	37.4	50.4	48.4	16.6	13.2	28.0		34.4	7.9
Levator scapulae	43.3	44.3	46.9	22.7	17.8	†		37.8	6.3
Rhomboideus	69.2	80.0	102.6	44.7	27.8	†		68.0	24.8
Lat. dorsi	212.9	299.5	368.7	‡	64.3	216.0		217.6	82.8
Trapezius	145.8	313.6	250.4	100.0	76.1	†		187.9	34.7
Teres major	98.0	140.7	129.8	123.0	26.0	97.0		85.7	31.7
Teres minor	†	38.5	27.3	130.4†	67.0	20.0		21.7	12.6
Infraspinatus	131.7†	160.0	181.4	†	‡	99.0		116.8	13.8
Supraspinatus	48.0	78.7	59.0	‡	26.4	47.0		43.6	8.6
Subscapularis	164.3	177.5	233.9	83.8	62.4	131.0		135.8	24.4
Deltoideus	304.6	439.8	468.4	141.9	130.5	244.0		297.0	55.8
Pect. major	239.9	365.0	415.0	92.2	63.5	199.0		199.8	40.9
Pect. minor	45.9	59.4	56.8	20.0	16.3	†		42.5	5.8
Serratus anterior	186.0	259.4	223.6	99.1	73.9	†		197.7	41.2
Weight left-hand side	1982.4	2806.3	3217.0	1092.2	797.4			1897.7	
		Right	Right			Right		Average	s.d.
Biceps		210.7	181.3			97.0	108.2§	111.2	20.2
Triceps		177.8	441.1			95.0*	127.8*	99.7*	10.1
Coracobrachialis		59.1		53.4		30.0	21.3	30.6	8.6
Levator scapulae		47.4	46.0					37.9	7.3
Rhomboideus		83.5	99.4				68.8	71.4	20.2
Lat. dorsi		361.8	‡			198.0	339.2	226.1	71.8
Trapezius		347.7	245.4				370.4	185.8	25.3
Teres major		140.5	525.0			101.0	70.5	88.3	25.9
Teres minor		30.5	26.1			23.0	24.6	28.3	6.1
Infraspinatus		178.0	180.2			104.0	85.2	109.8	16.2
Supraspinatus		76.8	50.9	49.0			39.3	36.2	7.2
Subscapularis		200.8	225.2			135.0	121.3	138.6	21.1
Deltoideus		473.8	472.8			254.0	386.7	314.4	72.9
Pect. major		408.5	431.1			235.0	286.8	202.6	38.7
Pect. minor		66.5	58.1				52.4	41.5	11.7
Serratus anterior		276.0	223.6				193.4	204.8	41.9
Weight right-hand side		3139.4	3259.6				2295.8	1927.1	
Total weight		5945.7	6476.6					3824.9	

*Long head only.
†Infraspinatus + teres minor.
‡Not available.
§Given as volumes with a density of $1\ g\,cm^{-3}$.

Coons surfaces (Wood *et al.*, 1989a). Wood *et al.*'s calculation methods led to considerable differences in which the PCSA values calculated from volume and muscle length were considerably lower. Next to data reported from Weber, data given by Fick also contain directly measured values, as well as Poppen and Walker's data extension. Despite differences in measurement method, data of Bassett agreed well with our data ($r=0.938$, coeff. $=1.002$) probably indicating the usefulness of indirect calculations. On the other hand, data from Weber and Shiino differed significantly from our results (t-test correlated samples; $p<0.05$ and $p<0.01$ respectively), possibly indicating postural differences.

Data on muscle masses have been published by Weber (1851), Bischoff (1863), Theile (1884) and Shiino (1913), although Shiino expressed his doubts on the accuracy of measurements on cadavers which were not completely fresh. Theile published a vast amount of data on the masses of body components but generally omitted to determine bodyweight. For this reason data from only three of his specimens are reported here (Table 6). Results of Theile (specimens III and XLI) and Bischoff differed significantly from this study (t-test, $p<0.01$). These differences disappeared when normalized for total muscle mass. Data reported by Wood *et al.* (1989a) are volume data. The authors state, however, that muscle masses could be calculated with the use of a muscle density value of $1\ \mathrm{g\,cm^{-3}}$.

As already mentioned in the Introduction, the purpose of this article was to describe the method of data collection and results from descriptive anatomy in the process of development of a three-dimensional model of the shoulder mechanism. Van Der Helm *et al.* (1991) describe the method of and results on the calculation of positions of muscle and ligament attachments, muscle paths and positions of rotation centres of articulations involved.

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REFERENCES

Barter, J. T. (1957) Estimation of the mass of body segments. Wright Air Development Center, TR-57-260, Wright-Patterson Air Force Base, Ohio.

Bassett, R. W. (1983) A three-dimensional study of the moments and potential forces in the abducted externally rotated shoulder. M.Sc. thesis, University of Minnesota.

Bearn, J. G. (1967) Direct observations of the function of the capsule of the sternoclavicular joint in clavicular support. *J. Anat.* **101**, 159–170.

Bischoff, E. (1863) Einige Gewichts- und Trocken-Bestimmungen der Organe des menslichen Korpers. *Z. rationelle Med.* **20**, 77–118.

Braune, W. and Fischer, O. (1888) Uber den Anteil, den die einzelnen Gelenke des Schultergurtels am der Beweglichkeit des menslichen Humerus haben. *Abh. Math–Phys. cl.d.k. Sachs Gesellsch. d. Wiss.* **14**, 393–410.

Chandler, R. F., Clauser, C. E., McConville, J. T., Reynolds, H. M. and Young, J. W. (1975) Investigation of inertial properties of the human body. DOT HS-801 430, Wright Patterson Air Force Base, Ohio.

Clarijs, J. P. and Marfell-Jones, M. J. (1986) Anatomical segmentation in humans and the prediction of segmental masses from intra-segmental anthropometry. *Hum. Biol.* **58**, 771–782.

Clauser, C. E., McConville, J. T. and Young, J. M. (1969) Weight, volume and center of mass of segments of the human body. AMRL-TR-69-70, Wright-Patterson Air Force Base, Ohio.

Conway, A. M. (1961) Movements at the sternoclavicular and acromioclavicular joints. *Phys. Ther. Rev.* **11**, 421–432.

Dempster, W. T. (1955) The anthropometry of body action. *Ann. N. Y. Acad. Sci.* **63**, 559–585.

Dempster, W. T. (1955) Space requirements of the seated operator. WADC-TR-55-159, Wright Patterson Air Force Base, Ohio.

Depalma, A. F. (1973) *Surgery of the Shoulder*, 2nd Edn. Lippincott, Philadelphia.

Dvir, Z. and Berme, N. (1978) The shoulder complex in elevation of the arm: a mechanism approach. *J. Biomechanics* **11**, 219–225.

Engen, T. J. and Spencer, W. A. (1968) Method of kinematic study of normal upper extremity movements. *Arch. Phys. Rehab. Med.* **49**, 9–11.

Engin, A. E. and Peindl, R. D. (1987) On the biomechanics of human shoulder complex—I. Kinematics for determination of the shoulder complex sinus. *J. Biomechanics* **20**, 103–117.

Fick, R. (1911) *Handbuch der Anatomie und Mechanik der Gelenke*, Teil 3. Gustav Fischer, Jena.

Fick, A. E. and Weber, E. (1877) Anatomisch-mechanische Studie uber die Schultermuskeln. *Verh. der phys.-med. Ges. zu Wurzburg* **XI**, 123–153.

Freedman, L. and Munro, R. (1966) Abduction of the arm in the scapular plane and glenohumeral movements. *J. Bone Jt Surg.* **48A**, 1503–1510.

Friedel, A. (1926) Die Gestaltung des Schulterblattes. *Z. mikro-anatom. Forsch.* **5**, 315–338.

Fukuda, K., Graig, E. V., An, K. N., Cofield, R. H. and Chao, E. Y. S. (1986) Biomechanical study of the ligamentous system of the acromioclavicular joint. *J. Bone Jt Surg.* **68A**, 434–439.

Hinrichs, R. N. (1985) Regression equations to predict segmental moments of inertia from anthropometric measurements: an extension of the data of Chandler *et al.* (1975). *J. Biomechanics* **18**, 621–624.

Hogfors, C., Sigholm, G. and Herberts, P. (1987) Biomechanical model of the human shoulder—I. Elements. *J. Biomechanics* **20**, 157–166.

Howell, S. M., Imobersteg, A. M., Seger, D. H. and Marone, P. J. (1986) Clarification of the role of the supraspinatus muscle in shoulder function. *J. Bone Jt Surg.* **68A**, 398–404.

Hvorslev, C. M. (1927) Studien ueber die Bewegungen der Schulter. *Skand. Arch. f. Physiol.*, Separatabdruck.

Inman, V. T. and Saunders, J. B. (1946) Observations on the functions of the clavicle. *California Med.* **65**, 158–166.

Inman, V. T., Saunders, J. B. and Abbott, L. C. (1944) Observations on the function of the shoulder joint. *J. Bone Jt Surg.* **26A**, 1–30.

Jensen, R. H. and Davy, D. T. (1975) An investigation of muscle lines of actions about the hip: a centroid appoach vs the straight line approach. *J. Biomechanics* **8**, 103–110.

Kaleps, I., Clauser, C. E., Young, J. W., Chandler, R. F., Zehner, G. F. and McConville, J. T. (1984) Investigation into the mass distribution properties of the human body and its segments. *Ergonomics* **27**(12), 1225–1237.

Kennedy, J. C. and Cameron, H. (1954) Complete dislocation of the acromioclavicular joint. *J. Bone Jt Surg.* **36B**, 202–208.

McConville, J. T., Churchill, T. D., Kaleps, I., Clauser, C. E. and Cuzzi, J. (1980) Anthropometric relationships of body and body segment moments of inertia. Aerospace Medical Research Laboratory Report No. AFAMRL-TR-80-119, Wright-Patterson Air Force Base, Ohio.

Meijers, K. A. E. (1961) A study of the articulation of the shoulder (in Dutch). Ph.D. thesis, University of Leiden.

Miller, D. I. and Morrison, W. E. (1975) Prediction of segmental parameters using the Hanavan human body model. *Med. Sci. Sports* **7**, 207–212.

Mollier, S. (1899) *Ueber die Statik und Mechanik des menslichen Schultergurtels unter normalen und pathologischen Verhaltnissen.* Festschr. f. C. v. Kupffer, Jena.

Moseley, H. F. (1972) *Shoulder Lesions.* Churchill Livingstone, London.

Oxnard, C. E. (1967) The functional morphology of the primate shoulder as revealed by comparative anatomical, osteormetric and discrimination function techniques. *Am. J. Phys. Anthropol.* **26**, 219–240.

Peindl, R. D. and Engin, A. E. (1987) On the biomechanics of human shoulder complex—II. Passive resistance properties beyond the shoulder complex sinus. *J. Biomechanics* **20**, 119–134.

Peterson, B., Hogfors, C., Herberts, P., Selvik, G. and Sigholm, G. (1985) The shoulder rythm. In *Abstract Book 218, 10th ISB Congr.*, Umea, Sweden.

Pfuhl, W. (1934) Der Bewegungsumfang im Schultergelenk und der Anteil des subacromialen Nebengelenkes an den Schulterbewegungen. *Morph. Jb.* **74**, 670–696.

Poppen, N. K. and Walker, P. S. (1976) Normal and abnormal motion of the shoulder. *J. Bone Jt Surg.* **58A**, 195–200.

Poppen, N. K. and Walker, P. S. (1978) Forces at the glenohumeral joint in abduction. *Clin. Orthop. Rel. Res.* **135**, 165–170.

Pronk, G. M. (1988) Three-dimensional determination of the position of the shoulder girdle during humerus elevation. In *Biomechanics XI-B, 11th ISB Congr.*, pp. 1070–1076, Amsterdam.

Pronk, G. M. (1989) A kinematic model of the shoulder girdle: a resumé. *J. Med. Eng. Technol.* **13**, 119–123.

Pronk, G. M. and Van Der Helm, F. C. T. (1991) The palpator, an instrument for measuring the three-dimensional positions of bony landmarks in a fast and easy way. *J. Med. Eng. Technol.* (submitted).

Saha, A. K. (1961) *Theory of Shoulder Mechanism: Descriptive and Applied.* Thomas, Springfield, IL.

Saha, A. K. (1971) Dynamic stability of the glenohumeral joint. *Acta orthop. scand.* **72**, 491–505.

Saha, A. K. (1973) Mechanics of elevation of the glenohumeral joint. *Acta orthop. scand.* **44**, 668–678.

Salter, E. G., Nasca, R. J. and Shelly, B. S. (1987) Anatomical observations on the acromioclavicular joint and supporting ligaments. *Am. J. Sports Med.* **15**, 199–206.

Shiino, K. (1913) Schultergelenkbewegungen und Schultermuskelarbeit. *Arch. Anat. Physiol.* (Suppl.) A 1–88.

Theile, F. W. (1884) Gewichtsbestimmungen zur Entwickelung des Muskelsystems und Skelettes beim Menschen. *Ksl. Leop.-Carol.-Deutchen Akad. d. Naturforscher* **46**, 139–471.

Urist, M. R. (1946) Complete dislocations of the acromioclavicular joint. *J. Bone Jt Surg.* **28**, 813–837.

Van Der Helm, F. C. T. (1988) A dynamic model of the shoulder girdle. In *Proc. 6th Mtg Eur. Soc. Biomech.*, Bristol.

Van Der Helm, F. C. T. and Pronk, G. M. (1989) A fine element musculoskeletal model of the shoulder mechanism. *2nd Int. Symp. Comput. Simul. Biomech.*, Davis, CA.

Van Der Helm, F. C. T., Veeger, H. E. J., Pronk, G. M., Van Der Woude, L. H. V. and Rozendal, R. H. (1991) Geometry parameters for musculoskeletal modelling of the shoulder mechanism. *J. Biomechanics* (submitted).

Veldpaus, F. E., Woltring, H. J. and Dortmans, L. J. M. G. (1988) A least squares algorithm for equiform transformation from spatial marker coordinates. *J. Biomechanics* **21**, 45–54.

Wallace, W. A. (1982) The dynamic study of shoulder movement. In *Shoulder Surgery* (Edited by Bailey, I. and Kessel, L.), pp. 139–143. Springer, Berlin.

Wallace, W. A. and Johnson, F. (1982) A biomechanical appraisal of the acromioclavicular joint. In *Shoulder Surgery* (Edited by Bailey, I. and Kessel, L.), pp. 179–182. Springer, Berlin.

Weber, E. F. (1851) Ueber die Langenverhaltnisse der Fleischfasern der Muskeln im Algemeinen. *Berichte u. d. Verh. d. Konigl. Sachs. Ges. d. Wiss. Math.-Phys. Cl.* **1851**, 5–86.

Weijs, W. A. and Hillen, B. (1985) Cross-sectional areas and estimated intrinsic strength of the human jaw muscles. *Acta Morphol. Neerl.-Scand.* **23**, 267–274.

Wood, J. E., Meek, S. G. and Jacobsen, S. C. (1989a) Quantification of human shoulder anatomy for prosthetic arm control—I. Surface modelling. *J. Biomechanics* **22**, 273–292.

Wood, J. E., Meek, S. G. and Jacobsen, S. C. (1989b) Quantification of human shoulder anatomy for prosthetic arm control—II. Anatomy matrices. *J. Biomechanics* **22**, 309–325.

Yeadon, M. R. and Morlock, M. (1989) The appropriate use of regression equations for the estimation of segmental inertia parameters. *J. Biomechanics* **22**, 683–689.