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The moment arms of 23 muscle segments of the upper limb with varying elbow and forearm positions: Implications for motor control

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Abstract

In this study we examined moment arms of the complete muscle system of the elbow, including the wrist flexors that have their proximal attachment point on the humerus. This study was performed with the aim to identify the synergistic mover functions of the muscles as an anatomical basis for the study of motor control of the elbow. The upper limbs of three cadaver specimens were dissected. Muscles were replaced by elastic strings. The relationship between muscle length and joint angles (elbow flexion–extension (F–E) and forearm pronation–supination (P–S)) were determined. The first derivation of the relationship revealed the moment arms. The results confirmed the literature with respect to the major elbow flexors, extensors, pronators and supinators. Two wrist muscles had a substantial moment arm at the elbow: The *flexor carpi radialis* appears to be a pronator of the forearm, and the *extensor carpi radialis longus* is an elbow flexor. The ratios of moment arm between muscles and between the two orthogonal actions were relatively constant among the specimens. A mechanical explanation for the existence of subpopulations of motor units (i.e. differences in moment arm for the subpopulations) is viable for *supinator*, *brachialis*, and *brachioradialis*, whereas it is less viable for *biceps brachii*. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The upper limb is often used as a model to study motor control because of the 'redundancy of degrees of freedom problem' formulated by Bernstein (1967). The elbow joint may be considered a compound joint, containing three pairs of articular surfaces (humeroulnar, radiohumeral, and radio-ulnar) within its joint capsule. Fifteen muscles have actions involving motion at these joints. In theory, the number of solutions for performance of a particular motor task involving elbow movement is infinite; a wide variety of joint movements produced by a wide variety of muscle activation patterns, can be used to perform a single task. Yet, the neuro-motor system seems to have few problems dealing with this redundancy of choices. Many hypotheses have been formulated to deal with this issue (see Gielen et al., 1995 for a review). One of the theories regards the anatomical and mechanical constraints of the musculoskeletal system, including constraints regarding stabilisation of joints (e.g. Kumar et al., 1989), stress distribution in joints (Pauwels, 1980) and biarticular muscle actions in multi-joint movements (van Ingen Schenau, 1989).

To understand the impact of these mechanical constraints on motor behaviour the mechanical system needs to be described quantitatively. In this respect, reliable estimates of moment arms of muscles are crucial so that muscle performance (force and moment generation) can be estimated accurately. In many studies, moment arms of muscles of the elbow have been investigated (e.g. Braune and Fischer, 1889; Wilkie, 1950; Murray et al., 1995; An et al., 1981; Zuylen et al., 1988a; Kawakami et al., 1994). Most studies on the elbow system investigated only a few muscles (e.g. Murray et al., 1995; Zuylen et al., 1988a; Kawakami et al., 1994) or investigated the changes of moment arms with joint angles using simplistic (trigonometrical) models of the elbow assuming a fixed centre of rotation in the centre of the trochlea (e.g. Wilkie, 1950; An et al., 1981; Zuylen et al., 1988a; Kawakami et al., 1994). Particularly, the interaction of elbow flexion angle and forearm position (supination–pronation (S–P)) on moment arms is an interesting issue that has hardly been investigated. Murray et al. (1995) found that the biceps moment arm for elbow flexion changed with forearm position. Their data, however indicate that the interaction effects are relatively small and may be functionally insignificant. Yet, interactions of similar magnitude may be of enormous functional importance for muscles with a small moment arm in the pronation–supination (P–S) action. Furthermore, interindividual differences regarding the details of effects of joint positions on moment arms are important for understanding interindividual differences in muscle activity patterns during motor tasks of the elbow.

In this study we aimed to investigate moment arms of the complete muscle system of the elbow and forearm, including the wrist flexors that have their proximal attachment point on the humerus. This study was performed with the aim to identify the synergistic mover functions of the muscles. We concentrated on elbow and forearm positions around the mid-range of motion for two reasons. First, positions in the mid-range of motion are the most frequently occurring ones during daily life and many laboratory research situations (e.g. Jamison and Caldwell, 1993; Zuylen et al., 1988b; Sergio and Ostry, 1995). Secondly, our methodology of measurement involved replacing muscle segments with quasi-volumeless strings. For the mid-range of motion, it can be reasonably assumed that higher order effects caused by muscle volume, and not accounted for by our methods, are small.

The purpose of the present investigation was to determine the relationships between elbow and forearm positions and distances between muscle attachment sites. The measured length changes of representative parts of muscles crossing the elbow joint, in cadaver specimens, allowed calculation of moments arms of the muscles. Of particular interest were the analyses of interaction effects of elbow and forearm position on muscle moment arms and interindividual differences.

2. Methods

2.1. Model

To determine moment arms for elbow and forearm movements, the function $l = f(a)$, where l is the 23-dimensional vector of muscle lengths, and a the two-dimensional vector of joint angles, was estimated by a third order polynomial including cross-product (2nd and 3rd order). Main effects of joint angles were determined by truncation of the polynomial, i.e. excluding the cross-product from the fitting Eq. (1b). The moment arms are the Jacobian matrix of $l = f(a)$. Thus, the general equation was:

$$l = a_3 * \varepsilon^3 + a_2 * \varepsilon^2 + a_1 * \varepsilon + b_3 * \phi^3 + b_2 * \phi^2 + b_1 * \phi + c_3 * \varepsilon * \phi^2 + c_2 * \varepsilon^2 * \phi + c_1 * \varepsilon * \phi + O, \tag{1a}$$

$$l = a_3 * \varepsilon^3 + a_2 * \varepsilon^2 + a_1 * \varepsilon + b_3 * \phi^3 + b_2 * \phi^2 + b_1 * \phi + O, \tag{1b}$$

where $a_3, a_2, \ldots, c_2, c_1, O$ are the fitting parameters. A third order polynomial was chosen as a compromise between sufficient degrees of freedom in the model to properly describe changes in moment arms and sufficient reduction of noise in the data (see Spoor et al., 1990). For the fitting procedures all angles were expressed in radians. Partial derivation of the equation results in the flexion–extension (F–E) and P–S moment arms as function of elbow angle and forearm, position, respectively:

$$\delta l/\delta\varepsilon = 3a_3 * \varepsilon^2 + 2a_2 * \varepsilon + a_1 + c_3\phi^2 + 2c_2\phi * \varepsilon + c_1\phi \qquad \text{(including cross-product)},$$

$$\delta l/\delta\phi = 3b_3 * \phi^2 + 2b_2 * \phi + b_1 + 2c_3\varepsilon * \phi + c_2\varepsilon^2 + c_1\varepsilon,$$

$$\delta l/\delta\varepsilon = 3a_3 * \varepsilon^2 + 2a_2 * \varepsilon + a_1 \qquad \text{(excluding cross-product)},$$

$$\delta l/\delta\phi = 3b_3 * \phi^2 + 2b_2 * \phi + b_1.$$

When the interaction is included in the fit (full third order expansion) the moment arms for one action (i.e. F–E or P–S) differs as a function of both joint angles. The joint angles and moment arms were defined as follows. The included angle was used as a measure for elbow angle, i.e., full elbow extension is about 180°. Supination was defined as a positive angle and pronation as a negative angle, the mid-prone position being zero. Thus, differentiation of Eqs. (1a) and (1b) results in flexion and pronation moment arms that are positive, and extension and supination moment arms that are negative.

2.2. Experimental techniques and protocol

The upper limbs of three cadaver specimens (embalmed in a formaldehyde solution for at least six months) were dissected by removing muscles after the attachment points were indicated and marked. For muscles with large attachment sites, they were divided into segments, named by the proximo-distal positioning of the proximal attachment site (see Table 1). The division and location of attachment sites of muscle segments was based on the size of the whole attachment site. Thus, the proximal segment represented the most proximally placed fibre bundle of the muscle, the distal segment represented the most distally placed bundle, and the intermediate segment represented the geometric average in the proximo-distal direction. The ligaments of all joints were left intact as much as possible. In some cases, ligaments and interosseus

Table 1
The muscles and their segments investigated in this study

Muscle	Segments	Abbreviation
Triceps Brachii Long Head	–	TBlh
Triceps Brachii Medial Head	Proximal	TBm-p
	Distal	TBm-d
Triceps Brachii Lateral Head	Proximal	TBl-p
	Distal	TBl-d
Biceps Brachii, Long Head	–	BBl
Biceps Brachii, Short Head	–	BBs
Brachialis	Proximal	B-p
	Intermediate	B-i
	Distal	B-d
Brachioradialis	Proximal	BR-p
	Distal	BR-d
Supinator	Proximal	S-p
	Intermediate	S-i
	Distal	S-d
Pronator Teres	–	PT
Pronator Quadratus	Proximal	PQ-p
	Distal	PQ-d
Flexor Carpi Radialis	–	FCR
Flexor Carpi Ulnaris	–	FCU
Extensor Carpi Radialis Longus	–	ECRl
Extensor Carpi Radialis Brevis	–	ECRb
Extensor Carpi Ulnaris	–	ECU

membranes had to be removed (partly) to allow sufficient movement in the joints of the fixated specimens. Care was taken that this procedure did not lead to disruption of the joints. The scapula was fixated onto the humerus in the anatomical position by a screw connecting the acromion and the head of the humerus. All muscles were replaced by elastic strings which were attached to the bones by small screws (Ø 3 mm). The strings representing muscles of the wrist were attached to the radius or ulna at the level of the carpal grooves/tunnels. The hand was fixated to the radius in the anatomical position by means of a metal plate connecting the third metacarpal bone to the radius.

The elbow and forearm angles were measured by steel rods that were connected onto the humerus and ulna, and ulna and radius, respectively (Fig. 1(A)). The angles between these rods were measured by adapted goniometers (accuracy 1°), minimising parallax in case the two rods did not run in exactly the same plane. At reference angles of elbow (120°) and forearm (midprone) the angles between the rods were measured to allow conversion from

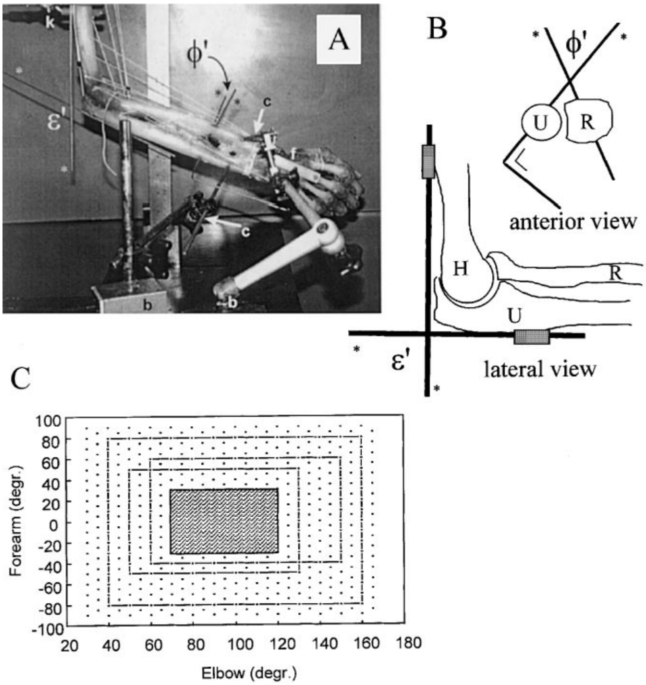

Fig. 1. (A) Experimental setup. The femur was held by two clamps (one visible, marked ‘k’). Two rods marked ‘c’ were used to fix the radius and ulna in the required position with the aid of magnetic bases ‘b’. Four rods marked ‘*’ were used to measure elbow angle and forearm position. The metal plate fixing hand and radius is marked ‘f’. (B) Schematic representation of measurement of elbow angle (ε') and forearm position (ϕ'), using rods attached to humerus (H), radius (R), and ulna (U). Angles were converted to true angles (ε, ϕ) as described in the text. In the case that the two rods through the mid-shaft of radius and ulna were almost parallel, a 90° angled rod was used. (C) The matrix of combinations of elbow angle and forearm position that were measured (three open boxes) and the range that was used in the statistical analysis (filled box).

the measured rod angles (ε', ϕ'; Fig. 1(B)) to actual elbow (ε) and forearm (ϕ) angles. The elbow angle was measured between humerus (acromion – lateral epicondyle) and forearm (olecranon – styloid process ulna), and the forearm position by position of the styloid processes of ulna and radius in the vertical plane.

The humerus was fixed vertically in a stand. The ulna and radius were connected via rods to magnetic bases. The magnetic bases allowed easy alteration of elbow and forearm positions, yet providing a stable fixation during measurement (Fig. 1(A)). The elbow angle was changed in steps of 5° between measurements. The forearm angle was changed in steps of 10° at each elbow joint angle. At each subsequent elbow angle position, the starting forearm joint angle differed 5° from the previous one. Thus a matrix of elbow and forearm measurement positions was obtained with a joint angle step of 5° (Fig. 1(C)). Given the ranges of joint angles in all specimens (Fig. 1(C)), it was decided to investigate the moment arms for a joint angle range of 70–120° elbow flexion, and −30° to 30° forearm position. This range ensured that errors caused by deviation of the curve fittings from the data at the data borders (Ettema, 1997) did not occur.

In each position of the elbow and forearm, the lengths of the elastic strings were measured using a flexible metal tape ruler. The muscle attachment sites (i.e. start and end of strings) were defined as the centre of the screw heads, which were clearly marked. Thus, string lengths were measured between the centres of the attachment screws, along the pathway of the string. Where the strings followed a strong curvature or were partly unapproachable with the ruler the following solution was used: part of the string was made of inelastic rope, connected to an end-piece of elastic string. Thus, only a measurable, elastic, and clearly marked part of the string needed to be measured to determine length changes with joint angles. The scale division of the ruler was 1 mm, and the muscle lengths were rounded to the nearest 0.5 mm. Thus, the reading error amounted to between 0.25 and 0.5 mm.

After the termination of these measurements, osteometric measurements were taken of humerus, ulna and radius, according to Martin (1957).

2.3. Statistics

The effects of elbow, forearm and cross-product (linear, quadratic, and cubic components lumped) on muscle length were tested for each specimen by means of ANOVA of the full third order polynomial fit ($p < 0.05$). Any significance was interpreted as the actual existence of a moment arm for the specimen, muscle and joint of interest. It should be noted that this does not imply that such moment arm exists throughout the range of movement.

3. Results

3.1. General trends

Fig. 2 shows examples of polynomial curve fittings and 95% confidence intervals (full expansion fit) for four muscles. Muscle lengths are plotted in two

Table 2
Moment arms for elbow F–E and forearm P–S at three different angles. Adjusted R^2 and the sum of squares accounted for as percentage of the residual sum of squares (SScp%) is also given

		TBlh	TBm-p	TBm-d	TBl-p	TBl-d	BBl	BBs	B-d	B-i	B-p	BR-d	BR-p	S-p	S-i	S-d	PT	PQ-p	PQ-d	FCR	FCU	ECRl	ECRb	ECU
Elbow		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
#1	70	−15.4	−16.1	−15.0	−16.3	−17.6	41.5	42.4	18.5	28.4	43.5	52.4	78.6	7.5	−0.9	−0.6	21.4	−0.9	−0.4	6.5	5.6	23.6	3.4	3.2
	95	−17.5	−19.2	−19.3	−20.8	−22.6	44.6	46.2	17.2	29.5	38.5	49.7	76.3	6.3	−0.1	−0.6	25.0	−1.6	0.2	7.8	5.4	20.4	1.3	4.2
	120	−20.3	−21.1	−22.4	−24.8	−24.0	36.3	37.8	14.5	24.3	27.1	37.1	57.4	4.9	0.9	0.1	22.4	−1.4	1.2	4.0	1.1	14.1	0.7	3.3
		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
#2	70	−14.1	−13.6	−10.4	−11.1	−10.4	48.9	44.6	16.6	32.3	43.5	56.3	68.8	12.7	−0.2	0.0	10.5	0.0	0.9	6.2	6.0	30.4	15.8	14.6
	95	−27.2	−23.7	−23.3	−27.8	−25.0	61.7	59.2	24.4	39.6	57.7	75.4	91.0	18.9	−1.4	−1.7	17.3	−0.1	1.9	5.4	3.7	35.7	17.0	14.4
	120	−36.1	−40.6	−45.2	−55.1	−41.5	56.8	60.9	30.4	33.9	44.3	63.9	79.9	20.4	4.4	0.8	37.4	1.1	−4.0	−4.1	−1.6	26.9	13.9	4.4
		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
#3	70	−29.0	−28.1	−26.9	−23.2	−26.9	64.1	62.1	35.1	58.9	63.1	89.8	175.5	21.8	−2.3	0.7	24.8	−1.3	−0.4	11.9	7.3	51.1	19.7	15.9
	95	−28.9	−29.9	−30.1	−27.8	−30.1	52.2	49.2	22.8	32.4	37.8	58.8	115.7	13.3	0.1	1.7	21.3	−0.4	0.3	6.6	3.9	31.4	11.3	7.6
	120	−23.3	−26.0	−24.6	−24.6	−24.6	32.5	30.5	13.6	15.2	17.7	29.6	59.3	4.5	0.4	1.5	17.4	−0.1	−0.1	2.5	1.4	14.7	2.4	1.3
Forearm							*	*				*	*	*	*	*	*	*	*	*	*	*	*	
#1	−30	0.0	0.1	0.0	0.0	0.1	−8.6	−8.8	0.0	−0.1	−0.2	−5.0	−7.8	−9.6	−5.3	−2.5	6.1	6.8	7.8	2.9	−1.2	−1.9	−1.5	−0.2
	0	0.0	0.0	0.0	0.0	0.0	−7.9	−8.0	−0.1	−0.1	0.0	−2.5	−4.3	−9.4	−4.5	−3.8	8.1	6.2	6.8	5.1	0.1	−0.6	−1.5	0.0
	30	−0.1	−0.2	0.0	0.0	−0.1	−6.2	−6.2	0.0	0.1	0.2	0.7	0.6	−8.7	−4.8	−5.2	9.0	4.1	5.4	6.4	1.8	0.5	−1.2	0.1
							*	*				*	*	*	*	*	*	*	*	*	*	*	*	*
#2	−30	0.5	0.2	1.2	0.7	0.5	−8.7	−11.0	−0.2	−0.7	−0.2	−7.4	−6.7	−6.2	−6.5	−1.6	6.0	4.6	8.1	4.8	−2.6	−2.5	−1.6	−1.6
	0	−0.1	−0.1	−0.3	−0.3	−0.3	−12.1	−10.3	0.1	0.3	0.1	−4.6	−2.8	−7.6	−7.2	−6.1	8.5	8.1	8.8	5.6	0.4	−0.7	−1.4	2.7
	30	0.0	0.1	0.1	0.0	0.1	−10.0	−8.9	0.0	0.0	−0.1	0.3	0.8	−7.6	−5.9	−6.6	8.7	7.7	6,6	5.3	2.1	1.6	0.6	3.4
							*	*				*	*	*	*	*	*	*	*	*	*		*	*
#3	−30	−0.1	−0.4	0.0	0.1	0.0	−6.6	−7.4	−0.6	−1.9	−1.4	−9.0	−8.0	−6.8	−4.9	−2.3	8.7	9.5	8.3	3.0	−0.2	−2.4	−3.4	0.6
	0	0.0	0.1	0.1	0.0	0.1	−7.3	−7.1	0.1	0.3	0.2	0.0	0.8	−3.2	−4.7	−2.5	9.0	9.7	7.8	6.6	1.0	0.6	−1.0	0.4
	30	0.0	0.1	0.0	0.0	0.0	−6.8	−6.3	0.1	0.3	0.2	5.8	4.6	−2.4	−5.0	−3.4	8.2	7.6	7.3	7.0	2.1	1.6	−0.3	1.2
#1	R^2-adj.	0.967	0.968	0.994	0.994	0.994	0.984	0.968	0.990	0.991	0.994	0.995	0.996	0.966	0.959	0.962	0.990	0.978	0.974	0.906	0.687	0.989	0.644	0.534

Table 2 (Continued)

		TBlh	TBm-p	TBm-d	TBl-p	TBl-d	BBl	BBs	B-d	B-i	B-p	BR-d	BR-p	S-p	S-i	S-d	PT	PQ-p	PQ-d	FCR	FCU	ECRl	ECRb	ECU
	SScp%	0.1	0.1	0.2	0.1	0.0	15.8*	27.7*	0.1	0.2	1.1	43.0*	58.2*	6.3	3.7	5.1	47.5*	23.1*	12.7*	16.2*	17.0*	62.4*	3.0	6.6*
#2	R^2-adj.	0.996	0.999	0.968	0.997	0.996	0.997	0.996	0.996	0.998	1.000	0.997	0.998	0.984	0.932	0.918	0.986	0.972	0.974	0.886	0.910	0.997	0.986	0.980
	SScp%	0.5	0.0	0.1	0.0	0.0	59.7*	79.0*	0.0	0.0	0.0	10.3*	59.4*	8.7	3.7	8.9	15.1*	3.6	4.5	6.7	15.4*	23.0*	4.3	3.1
#3	R^2-adj.	0.995	0.996	0.992	0.993	0.992	0.986	0.969	0.992	0.984	0.988	0.967	0.968	0.977	0.886	0.853	0.969	0.983	0.968	0.971	0.800	0.985	0.968	0.934
	SScp%	0.2	0.4	0.4	0.4	0.4	11.3	34.4*	0.1	0.8	1.1	4.6	5.4	4.9	1.1	8.1	21.0*	3.5	0.7	3.3	7.0	17.6*	63.7*	14.9

Moment arms are based on the truncated polynomial fit (excluding cross-product). R^2 is adjusted for degrees of freedom. (*) Significance for moment arms and the elbow-forearm interaction(cross-product) is based on statistical significance of effect of joint angle on muscle length (ANOVA of the polynomial fit, $p < 0.05$).

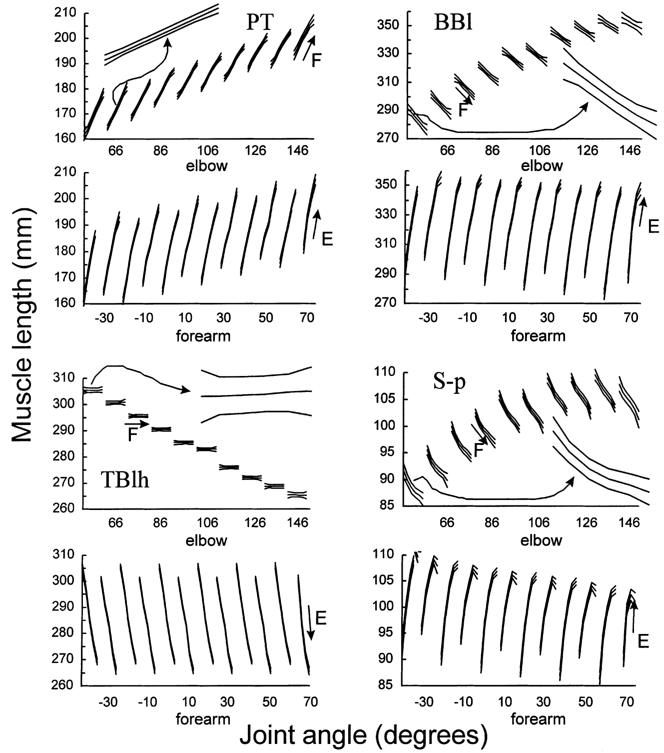

Fig. 2. Examples of full expansion polynomial fittings (and 95% confidence intervals) of muscle lengths as function of elbow angle and forearm position. Insets show enlargements of segments of the fittings. The data are presented in two ways. Primary joint angles are indicated on the horizontal axes, secondary joint angles forearm (F) and elbow (E) are indicated in the diagrams. The arrows indicate increasing angle and thus point towards extension (elbow) and supination (forearm). The tangents of segments indicate the moment arms for the respective joints. The 95% confidence intervals for the tangents were in the centre of the segments approximated by the 95% confidence intervals of the length curve. At mid-prone position and 95° elbow flexion the 95% interval were: PT, P–S: 9.01 – 7.60 mm; F–E: 22.49 – 21.09 mm. BBl, P–S: −5.77 – −8.89 mm; F–E: 51.81 – 48.69 mm. TBlh, P–S: 0.50 – −0.52 mm; F–E: −27.63 – −28.64 mm. S–P, P–S: −3.07 – −4.16 mm; F–E: 22.49 – 21.09 mm.

ways, indicating the length change with forearm position at different elbow angles (top diagrams) and indicating the length change with elbow angle at different forearm positions (bottom diagrams). The F–E and P–S moment arms are the respective tangents of the curves. The diagrams for *biceps brachii* (long head) and *pronator teres* seem to indicate interaction effects, i.e. the supination moment arm changes with elbow angle. The statistical analysis of these results is shown in Table 2.

All muscles of all three specimens were significantly affected by elbow angle, and thus had a significant moment arm in the F–E direction (Table 2). The *pronator quadratus* and the intermediate and distal segments of the *supinator* do not attach to the humerus. The effect of elbow angle on their lengths may be explained by detailed analysis of kinematics of the elbow. For example, the rotation axes of P–S and F–E are not completely orthogonal (Veeger et al., 1997) and may show some interdependence. However, the effects were small and not consistent over elbow angle and amongst specimens.

Apart from *triceps brachii* and *brachialis*, all muscles were affected by forearm position. However, the P–S moment arms for most of the wrist muscles (FCU, ECRl, ECRb and ECU) are small and inconsistent. It should be noted that in two specimens the *brachioradialis* acts as a supinator in forearm positions up to 30° Only one specimen showed the generally accepted pattern that the *brachioradialis* draws the forearm toward the mid-prone position (i.e. supinates in pronation position and vice versa; see Murray et al., 1995).

3.2. Interactions

Significant interactions were found for *biceps brachii*, *brachioradialis*, *pronator teres*, FCU and ECRl. The interaction that appeared to be substantial and of possible functional significance is shown in Fig. 3. The supination moment arm of *biceps brachii* decreases with elbow extension, which is in agreement with the review by Stroyan and Wilk (1993). A small effect of forearm position on the flexion moment arm is also indicated. In two specimens, the *brachioradialis* supination moment arm is lost in elbow extension. The *pronator teres* has its largest pronation moment arm when the elbow is flexed, whereas its flexion moment arm reduces slightly toward the supinated forearm position.

3.3. Proportions

For only one F–E moment arm was a clear correlation found with osteometric data that seemed to bear a direct physical relationship with the specific moment arms. The F–E moment arm of *brachioradialis* correlated well with maximum ulna and humerus length ($r = 0.998$ and 0.904, respectively). For the P–S moment arms some more apparent relationships were found. The P–S moment arms of the *brachioradialis, supinator* and *pronator teres* correlated well with the (average of sagittal and transverse) mid-shaft diameter of

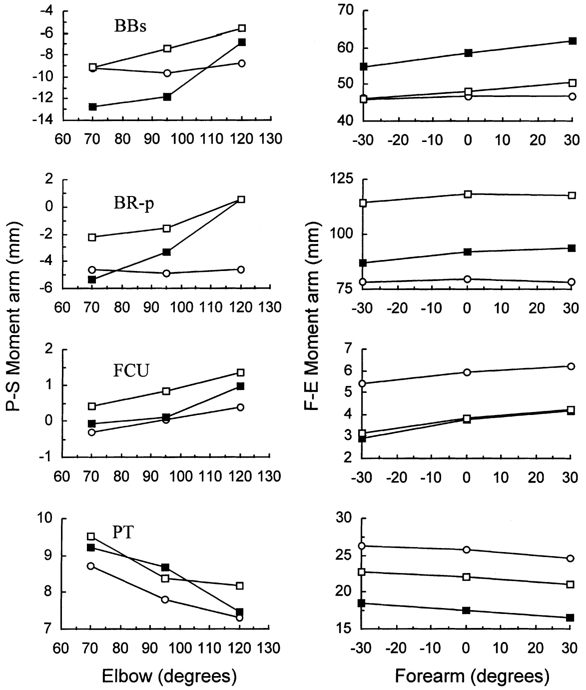

Fig. 3. Interaction of elbow angle and forearm position on moment arms. The P–S moment arms are at a mid-prone (0°) forearm position. The F–E moment arms are at an elbow angle of 95°; markers indicate the specimens.

the radius (r ranging from 1.000 to 0.927), whereas the P–S moment arms of the *pronator quadratus* and *flexor carpi radialis* correlated with the (maximal posterior–anterior) diameter of the ulna.

The relationships among moment arms of different muscles and between F–E and P–S moment arms are presented in Table 3 as ratios. Ratios were only calculated for moment arms that were statistically significant and consistently of substantial size (Table 2). In many cases, the ratios appeared to vary relatively little among specimens. However, the F–E over P–S ratio of the proximal part of the *supinator* and FCR, and the P–S ratios of *brachioradialis*, *pronator teres* and *pronator quadratus* over *biceps brachii*, varied widely around the equality value. Also shown in Table 3 are ratios of moments that can be generated by the muscles. The moments are based on cross-sectional areas reported by Yamaguchi et al. (1990), using data from An et al. (1979). Thus, these moment ratios can only be used as a rough in-

Table 3
Ratios of F–E moment arms over P–S moment arms (A), F–E moment arms (B) P–S moment arms, (C) between muscles

FE/PS	BBI	BBs	BR [a]	S-P	PT	FCR						
A												
Mean	6.00	5.93	6.47	*2.10*	2.74	*1.01*						
Sem	0.59	0.46	3.87	*0.74*	0.15	*0.26*						
Min	5.38	5.43	1.28	*0.67*	2.45	*0.48*						
Max	7.18	6.84	10.37	*3.18*	2.96	*1.28*						
FE	TB/BB	BBI/BBs	B/BB	BR/BB	S-P/BB	PT/BB	FCR/BB	FCU/BB	ECRl/BB	ECRb/BB	ECU/BB	Overall E/F
B												
Mean	0.50	1.01	0.66	1.51	0.25	0.46	0.11	0.08	0.57	0.18	0.15	–
Sem	0.03	0.02	0.01	0.16	0.05	0.05	0.03	0.01	0.06	0.07	0.03	–
Min	0.47	0.97	0.65	1.31	0.15	0.39	0.05	0.05	0.47	0.04	0.09	–
Max	0.56	1.05	0.68	1.82	0.31	0.55	0.15	0.10	0.67	0.28	0.20	–
Moment [b]	2.06		1.00	0.49	0.06	0.34	0.05	0.05	0.30	0.12	0.11	0.59
PS	BBI/BBs	BR/BB [a]	S/BB	PT/BB	PQ/BB	FCR/BB	ECRb/BB	Overall P/S				
C	S	S	S	P	P	P	S					
Mean	1.00	*0.89*	0.65	*1.01*	*0.91*	0.65	0.16	–				
Sem	0.01	*0.16*	0.07	*0.14*	*0.15*	0.09	0.04	–				
Min	0.99	*0.71*	0.57	*0.76*	*0.72*	0.81	0.23	–				
Max	1.02	*1.21*	0.79	*1.25*	*1.21*	0.51	0.08	–				
Moment [b]		*0.29*	0.48	*0.75*	*0.44*	0.28	0.11	0.78				

For all moment arms, absolute values were taken to calculate the ratios. The moment arms were averaged over all joint angles, except:

[a] Brachioradialis moment arm for forearm = –30° only. Where segments of muscles are not indicated. the average moment arms of the entire muscle were used. Ratios that showed wide range around 1 are shown in italics.

[b] The reported ratios moments are the product of moment arm and physiological cross-sectional area (An et al., 1979 and Yamaguchi et al., 1990). The cross-sectional are of S–P was taken as a third of the whole *supinator*. C: The muscles' actions, pronation (P) or supination (S), are indicated for clarity.

dication of the potential for the muscles to generate torque. However, these ratios once more stress the significance of ECRl and FCR in elbow flexion and pronation, respectively. The overall E/F and P/S ratios are based on the summation of all muscles in Table 3. It should be noted that when the *brachioradialis* was not included as a supinator (i.e. in mid-prone or supinated forearm position) the P/S ratio equals 0.99.

4. Discussion

The objective of this study was to provide a detailed description of the dependence of moment arms of muscles of the upper limb acting at the elbow and radio-ulnar articulations. The study included muscles that (presumably) have their main action at the wrist. The moment arm matrix was based on the estimated muscle length – joint angle matrix. This estimate may cause large errors in moment arm calculations (i.e. first derivation of the polynomial functions) at borders of the range of measured joint angles (Spoor et al., 1990; Ettema, 1997). Therefore, the interpretation of the results is limited to the mid-range of movement and should not be simply extrapolated to other angles. Some good correlations were found between osteometry and moment arms. Thus, the approach used by Murray et al. (1995) to model the elbow on the basis of osteometry seem viable. Still, interindividual differences regarding the exact location of attachment sites, which may be the cause of other poor osteometry – moment arm relationships, are not accounted for in the model by Murray et al. (1995).

It was assumed that the line of pull of each muscle segments was not affected by the volume of the muscles and surrounding tissues, including other muscles. This may not be the case during activities where many muscles of the upper limb are highly active. In such cases, muscle segments may have sufficient robustness to affect the line of pull of other segments and muscles. Yet, it would be hard to quantify such higher order effects.

4.1. General trends

Regarding the three major elbow flexors (BR, Brach, BB), the *brachioradialis* has the largest moment arm, and the *brachialis* the smallest, which is in agreement with the literature (e.g. Kawakami et al., 1994). The *triceps brachii* has about half the mechanical advantage of its antagonistic *biceps brachii* (see also Kawakami et al., 1994). The *pronator teres* seems to have a significant action in flexion, whereas the *supinator* is limited in elbow flexion. Furthermore, as documented by others (e.g. Braune and Fischer, 1889; Wilkie, 1950; An et al., 1981), the *extensor carpi radialis longus* must be regarded as a significant elbow flexor. The contributions of the muscles in flexion are in general agreement with the literature (Kawakami et al., 1994; Jørgensen and Bankov, 1971; Edgerton et al., 1986). The finding by An et al. (1981) that the *flexor carpi ulnaris* and *flexor carpi radialis* are extensors of the elbow was not confirmed in this study. In the movement of the forearm it appeared that the *biceps brachii* has the largest moment arm for supination with the *brachioradialis* playing a varying role (see below). Furthermore, the *flexor carpi radialis* appeared to be an important pronator. In total, five muscles (BB, BR, S–P, PT, FCR) can be described as bifunctional mover muscles with substantial moment arms at both the elbow and radio-ulnar articulation.

A small number of interaction effects were found between elbow angle and forearm position on P–S moment arms (Fig. 3). Thus, it seems justifiable to use relatively simple models, ignoring any interaction, to describe the elbow system as has been done in many studies. However, it should be noted that the present study only examined effects in the mid-range of motion. Furthermore, some of the interactions may be important regarding sophisticated motor actions.

4.2. Subpopulations within a muscle

With the exception of the *supinator*, only few and little differences were found among intramuscular segments regarding changes of moment arms with joint angles. Of course, effects of shoulder configuration on *triceps brachii* and *biceps brachii* actions were not considered in this study. Only the proximal segment of the *supinator*, originating from the humerus, has a moment arm for elbow flexion. The remainder of the muscle is a pure supinator of the forearm. The segments of the *brachioradialis* and *brachialis* show large absolute differences in moment arms, due to the large attachment sites, whereas the two heads of the *biceps brachii* show hardly any difference in this respect. Such information has direct implications for the interpretation of the existence of subpopulations of motor units within a muscle (e.g. Zuylen et al., 1988b; Theeuwen et al., 1996), also referred to as intramuscular task groups (Loeb, 1985). Task groups are described as a set of motor units (within a muscle or from several muscles) that are active simultaneously in a particular motor task, and by this task specificity are distinguishable from other motor units. Mechanical (moment arms), neural (linearising motor output) and physiological (fibre types) factors may correlate with the existence of task groups (see e.g. Loeb, 1985). Assuming that motor units are not randomly distributed within a muscle belly, the results of the current study would suggest that a mechanical correlation (i.e. differences in moment arm for the subpopulations) is viable for *supinator*, *brachialis*, and *brachioradialis*, whereas it is less viable for *biceps brachii* (see also Theeuwen et al., 1996). Even differences in motor activity between the two heads of the *biceps brachii* cannot be explained on mechanical grounds. Such differences may be explained by a different (stabilising) action at the shoulder (Kumar et al., 1989).

4.3. Biomechanical constraints of the synergy function

The *brachioradialis*, which is usually thought of as a muscle that pulls the forearm towards the mid-prone position, showed varying results among specimens. One specimen showed the previously described behaviour that is in agreement with the model by Murray et al. (1995). In two out of three specimens the neutral position of the forearm (i.e. where the BR P–S moment arm changes its sign) was 30° of supination. Such interindividual differences are important for the understanding of muscle activity patterns in motor tasks of the elbow with the forearm held in mid-prone position, such as studied by e.g. Jamison and Caldwell (1993) and Zuylen et al. (1988b)). The behaviour of the *brachioradialis* may differ considerably between subjects, depending on the neutral forearm position for this muscle in the P–S direction. Furthermore, the P/S ratios (Table 3) indicate that consideration of the *brachioradialis* as a supinator in mid-prone position may strongly affect the mechanical constraints, represented by the P/S overall ratio in Table 3. If the *brachioradialis* is considered as a supinator, the potential for the pronators to work as synergists for *biceps brachii* and *brachioradialis* in pure flexion tasks will be limited. It should be noted that the FCR, which contributes about 20% of the pronator torque, is included in the pronator group. Taking the changes of the P–S moment arms with forearm position (Table 1) into consideration, the limitations of this synergistic potential of the pronator muscles are likely to increase when moving the forearm into pronation. This is in agreement with elbow flexion strength that is reduced in the pronated forearm position (Jørgensen and Bankov, 1971; Kulig et al., 1984). In maximum flexion tasks the *biceps brachii* as well as of the *brachioradialis* are inhibited (up to 50% and 15%, respectively) with the forearm in the pronated position compared to the supinated position (Jørgensen and Bankov, 1971). The inhibition of the *biceps brachii* can be explained by its (undesired) supination action. However, inhibition of the *brachioradialis* can only be explained mechanically if the neutral forearm position for this muscle is towards supination.

Reciprocal inhibition of the major elbow flexors in different (dual) tasks may well be caused, in part, by the mechanical constraints of the musculoskeletal system. Cnockaert et al. (1975) compared F–S, F, and F–P isometric force tasks. They found highest activity of the *biceps brachii* and *brachioradialis* in F–S and lowest in F–P, which is in agreement with the suggestion made above. The fact that both muscles behaved in a similar manner may well indicate that in the subjects used, the *brachioradialis* was indeed a flexor–supinator, i.e. a full agonist of the *biceps brachii* in these particular tasks. Thus the hypothesis of dynamic F-torque sharing between *brachioradialis* and *biceps brachii* (Jamison and Caldwell, 1993) may have to be re-examined. Data from Jamison and Caldwell (1993) are not in full agreement with the suggestions made here, but may still point in a similar direction. They found inhibition of the *biceps brachii* during the F–S tasks, but only when the supination force was to be submaximal. A combination of generating maximal flexion torque and submaximal supination torque may be hard to accomplish with a fully active *biceps brachii*. Still, the mechanical constraints cannot explain why they (Jamison and Caldwell, 1993) did not find higher activity of *biceps brachii* and *brachioradialis* during F–S tasks compared to the F task.

The E/F overall ratio (0.59, Table 3) suggests a weaker extension potential than flexion, which is in agreement with most literature (review by Kulig et al., 1984) but not with Kawakami et al. (1994). However, as pointed out above, the generation of flexion torque is often inhibited by the P–S requirements. Such limitations do not exist for extension which only involves the uni-functional *triceps brachii* (although the long head is affected by shoulder position).

4.4. Biarticular wrist muscles

For two wrist muscles, i.e. the FCR and ECRl, the functional implications of their biarticularity should be considered. Like the *biceps brachii* and *triceps brachii* (long head) they may show activity patterns in multi-joint tasks that are principally different from monoarticular muscles. Biarticular muscles have the ability (by transporting work between joints) to avoid work dissipation during the control of external force and position in multi-joint tasks (e.g.

van Ingen Schenau, 1989; Jacobs and van Ingen Schenau, 1992; Gielen and van Ingen Schenau, 1992). This function may well be performed by the ECRl and FCR in tasks that involve the elbow and wrist.

Furthermore, when analysing motor tasks at the elbow, the constraints of the wrist need to be considered.

4.5. Proportions of moment arms

The invariable ratios of muscle moment arms (Table 3) may suggest that the human musculoskeletal system of the elbow and forearm is highly specialised for a particular set of (fine control) tasks requiring a certain set of musculoskeletal actuators that are finely tuned with respect to each other. Some parameters of the system can, of course, be modified by adaptation of muscle strength. A much larger sample than used in this study is required to substantiate such a hypothesis.

5. Conclusions

Clearly, a full and accurate description of the mechanical properties of the musculoskeletal lever system cannot explain all synergistic muscle behaviour described in the literature. Mechanical non-mover functions such as stabilisation of joints and stress distribution (muscles with small moment arms) need to be considered as well (e.g. Pauwels, 1980). However, like the comparison between physiological properties of antagonistic and synergistic muscles (e.g. Roy et al., 1984), a full description of moment arms of the musculoskeletal system is an essential component for the understanding of the organisation by the central nervous system.

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