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Muscle moment arm and normalized moment contributions as reference data for musculoskeletal elbow and wrist joint models

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ABSTRACT

A geometric musculoskeletal model of the elbow and wrist joints was developed to calculate muscle moment arms throughout elbow flexion/extension, forearm pronation/supination, wrist flexion/extension and radial/ulnar deviation. Model moment arms were verified with data from cadaver specimen studies and geometric models available in the literature. Coefficients of polynomial equations were calculated for all moment arms as functions of joint angle, with special consideration to coupled muscles as a function of two joint angles. Additionally, a "normalized potential moment (NPM)" contribution index for each muscle across the elbow and wrist joints in four degrees-of-freedom was determined using each muscle's normalized physiological cross-sectional area (PCSA) and peak moment arm (MA). We hypothesize that (a) a geometric model of the elbow and wrist joints can represent the major attributes of MA versus joint angle from many literature sources of cadaver and model data and (b) an index can represent each muscle's normalized moment contribution to each degree-of-freedom at the elbow and wrist. We believe these data serve as a simple, yet comprehensive, reference for how the primary 16 muscles across the elbow and wrist contribute to joint moment and overall joint performance.

1. Introduction

Musculoskeletal models serve as research tools to study the recruitment of individual muscles across multiple joints, the effect muscles have on joint moment, kinematics, and intersegmental forces, among many other applications (Delp and Loan, 1995). These models also serve as diagnostic tools which enable researchers to study the treatment and rehabilitation of joints in the body before and after tendon transfer surgeries (Herrmann and Delp, 1999; Loren et al., 1996). These subject-specific models allow assessment of musculotendon loss or damage to the overall joint moment capacity. Musculoskeletal models also provide insight into how individual muscles contribute to more than one motion (i.e., coupling), and how multiple muscles contribute to a specific motion (i.e., redundancy).

To establish accurate musculoskeletal models, musculoskeletal properties such as moment arm (MA) values, muscle geometries, and force generation characteristics are essential. While sources reporting moment arm values at the elbow and wrist from cadaver and geometrical models exist (An et al., 1981; Bremer et al., 2006; Loren et al., 1996; Murray et al., 1995, 2002; Ettema et al., 1998; Garner and Pandy, 2001; Gonzalez et al., 1996, 1997; Lemay and Crago, 1996; Murray et al., 1995; Pigeon et al., 1996), none are comprehensive and few provide a means to calculate MAs at multiple joint angles via polynomial regression coefficients. For instance, Ettema et al. (1998) investigated the interactions of elbow flexion angle and forearm position on MAs of several wrist muscles, however studied only a limited range of motion, excluded wrist *dfs* and did not provide fitting parameters to recreate measured MA curves. Thus, the motivation for this study was to provide a more complete *single source* dataset of two elbow-wrist musculoskeletal properties which include muscle MA values at varying angles and maximum potential moment contribution of the individual muscles.

Accordingly, we have developed a geometric musculoskeletal forearm–hand model that incorporates four degrees-of-freedom (*dfs*) across two joints (elbow and wrist) and 16 muscles (Fig. 1a caption). In an attempt to determine the moment capacity of a muscle, previous investigations have combined MA with the physiological cross-sectional area (PCSA) (An et al., 1981; Gonzalez et al., 1997; Ettema et al., 1998). Similarly, using anatomical muscle origin-insertion data with muscle-on-bone wrapping methods, we estimated individual maximum potential muscle moments based on each muscle's peak MA and PCSA. In addition, since regression equations provide the ability to compute muscle MAs with little computational cost (Menegaldo et al., 2004), coefficients of our MA results were calculated based on a comprehensive analysis of elbow and wrist MA–joint angle

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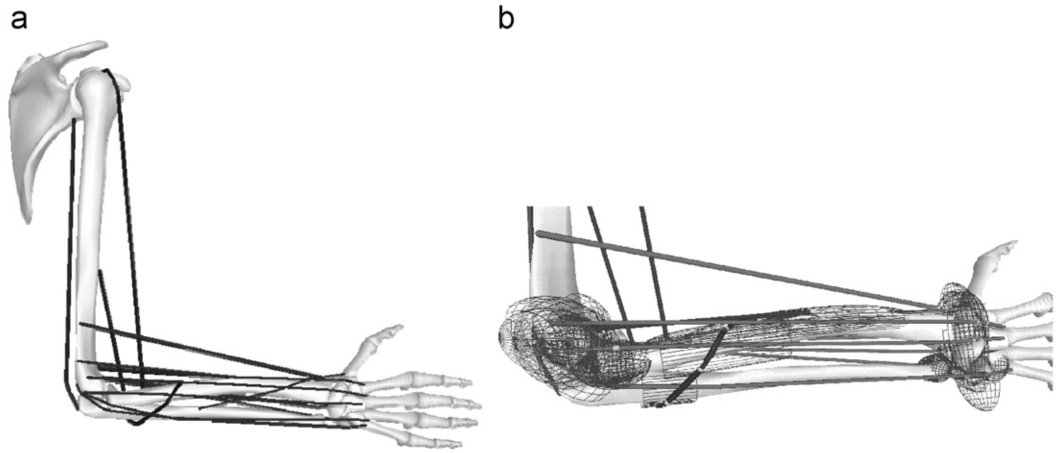

Fig. 1. (a) SIMM Arm model with 4 degrees-of-freedom; Elbow flexion/extension (EFE), forearm pronation/supination (PS), wrist flexion/extension (WFE) and wrist radial/ulnar deviation (RUD) and 16 musclulotendon units: triceps brachii (TRI), biceps brachii (BIC), brachioradialis (BRD), brachialis (BRA), pronator teres (PRO), supinator (SUP), extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), extensor carpi ulnaris (ECU), extensor digitorum communis (EDC), extensor digiti minimi (EDM), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), abductor pollicis longus (APL), and palmaris longus (PL). (b) SIMM Model (5 muscles—EDM, EDC, FCR, APL, and PL have been removed) displaying 31 wrap objects used to control muscle routing around joints and bone surfaces.

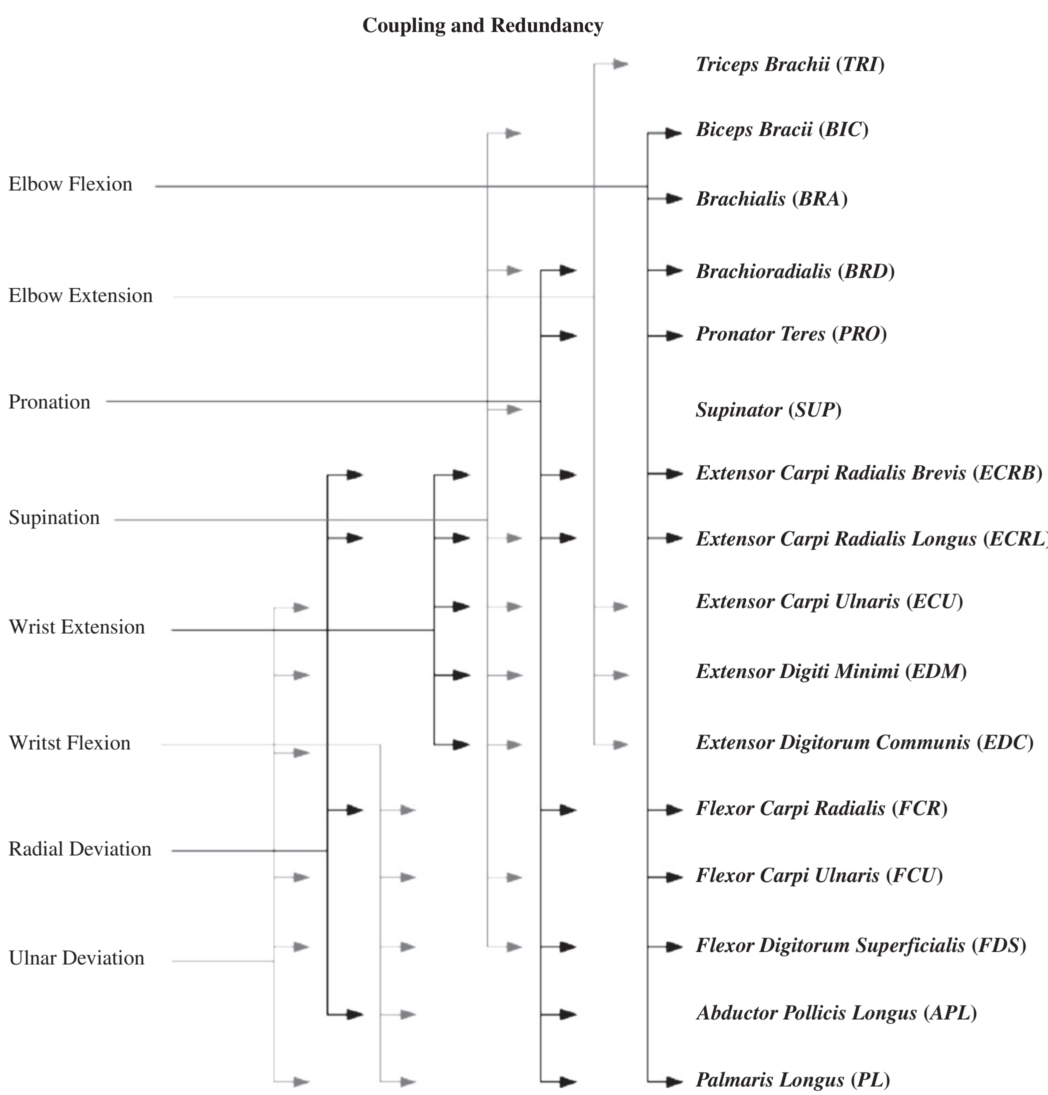

Fig. 2. *Coupling and redundancy*: (Agur and Dalley, 2005; Perkins, 2001). Anatomical origin and insertion sites were used to determine the actions of wrist muscles at the elbow. Muscle contribution to multiple motions demonstrates *coupling* and is shown with arrows aligned in rows next to the muscle name. Multiple muscles contributing to an individual motion demonstrates *redundancy* and is shown with arrows aligned in columns.