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Short communication

Modeling of the muscle/tendon excursions and moment arms in the thumb using the commercial software anybody

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ABSTRACT

A biomechanical model of a thumb would be useful for exploring the mechanical loadings in the musculoskeletal system, which cannot be measured *in vivo*. The purpose of the current study is to develop a practical kinematic thumb model using the commercial software Anybody (Anybody Technology, Aalborg, Denmark), which includes real CT-scans of the bony sections and realistic tendon/muscle attachments on the bones. The thumb model consists of a trapezium, a metacarpal bone, a proximal and a distal phalanx. These four bony sections are linked via three joints, i.e., IP (interphalangeal), MP (metacarpophalangeal) and CMC (carpometacarpal) joints. Nine muscles were included in the proposed model. The theoretically calculated moment arms of the tendons are compared with the corresponding experimental data by Smutz et al. [1998. Mechanical advantage of the thumb muscles. J. Biomech. 31(6), 565–570]. The predicted muscle moment arms of the majority of the muscle/tendon units agree well with the experimental data in the entire range of motion. Close to the end of the motion range, the predicted moment arms of several muscles (i.e., ADPt and ADPo (transverse and oblique heads of the adductor pollicis, respectively) muscles for CMC abduction/adduction and ADPt and FPB (flexor pollicis brevis) muscle for MP extension/flexion) deviate from the experimental data. The predicted moment potentials for all muscles are consistent with the experimental data. The findings thus suggest that, in a biomechanical model of the thumb, the mechanical functions of muscle–tendon units with small physiological cross-sectional areas (PCSAs) can be well represented using single strings, while those with large PCSAs (flat-wide attachments, e.g., ADPt and ADPo) can be represented by the averaged excursions of two strings. Our results show that the tendons with large PCSAs can be well represented biomechanically using the proposed approach in the major range of motion.

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1. Introduction

Biomechanical models of the hand can also be used to analyze the biomechanical consequences of surgical interventions, such as tendon (Xu, 2003) and ligament (Oka et al., 2003) repair and pulley reconstruction (Guelmi et al., 1997). Holzbaur et al. (2005) simulated the musculoskeletal surgery and analyzed neuromuscular control using a biomechanical model of upper extremity, which includes 15 degrees of freedom. A biomechanical model will be very useful in pre-surgical planning when tendon transfer procedure is considered (Cooney et al., 1984).

The kinematics of the musculoskeletal system of the thumb has been studied experimentally by Smutz et al. (1998). They measured the moment arms of four extrinsic muscles and four intrinsic muscles of the thumb as a function of the IP (interphalangeal), MP (metacarpophalangeal) and CMC (carpometacarpal) joint motions using six cadaver specimens. Although there are several biomechanical models of the thumb (e.g., Srinivasan and Landsmeer, 1982; Valero-Cuevas et al., 2003; Harley et al., 2004), most of them were mathematical models developed for specific cases and none of the previous studies have calibrated the model predictions on the muscle excursions with the experimental measurements for the entire range of motions. The goal of this study is to develop a generic, biomechanical model of the thumb and to calibrate the model predictions of the muscle/tendon kinematics with the experimental data by Smutz et al. (1998). The model will be developed using the commercial software AnyBody (version 2.0, AnyBody Technology, Aalborg, Denmark), such that it will become a tool for practical problems.

2. Methods

The thumb is modeled as a linkage system consisting of a trapezium, a metacarpal bone, a proximal and a distal phalanx (Fig. 1a). The trapezium bone is considered to be fixed. The dimensional scale of the bony sections is consistent

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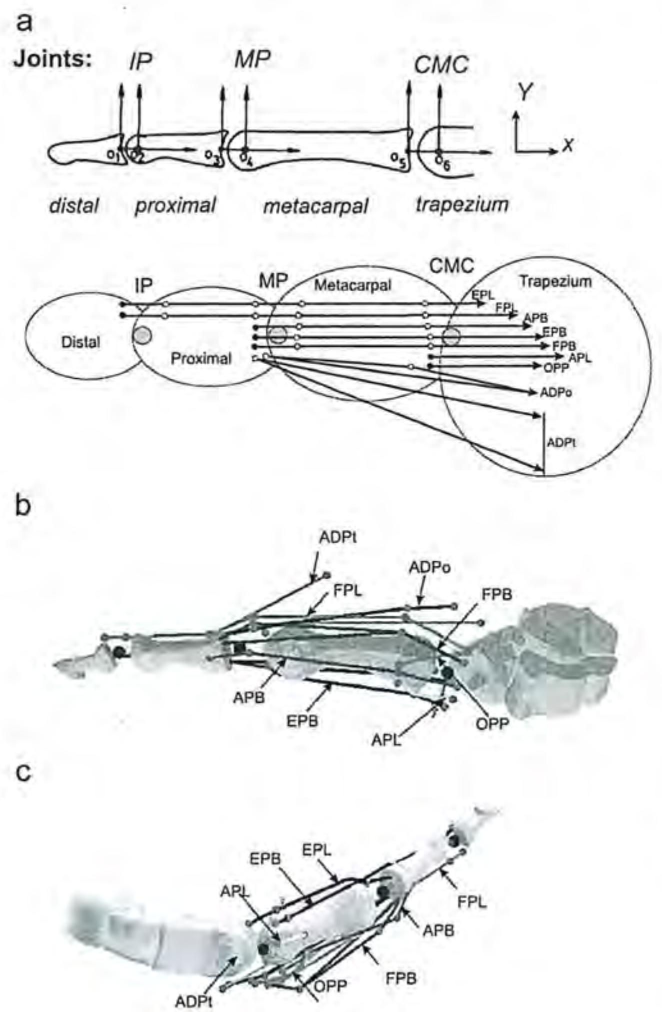

Fig. 1. Schematics of the proposed thumb model. (a) Definition of the coordinate systems in each bony section. (b) Schematics of the tendon network in the thumb model. The solid circles represent the tendon inserting locations, while the hollow circles represent the tendon pulley locations. (c) Schematics of the proposed thumb model developed using AnyBody. The model consists of a fixed trapezium, a metacarpal bone, a proximal and distal phalanx, which are linked via three joints: IP, MP and CMC. Nine muscles were included in the model: FPL, EPL, EPB, APL, FPB, APB, ADPt, ADPo and OPP.

with the normative model (An et al., 1979). These four bony sections are linked via three joints: IP, MP and CMC joints. The IP joint is modeled as a hinge with one DOF (degree-of-freedom), while the MP and CMC joints are modeled as universal joints with two DOFs. Nine muscles were included in the proposed model (Fig. 1b): flexor pollicis longus (FPL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), abductor pollicis longus (APL), flexor pollicis brevis (FPB), abductor pollicis brevis (APB), the transverse head of the adductor pollicis (ADPt), the oblique head of the adductor pollicis (ADPo) and opponens pollicis (OPP). The terminology describing the muscles in the study by Smutz et al. (1998) is adopted in the current study. The thumb model was developed on the platform of the commercial software package AnyBody (version 2.0) (Fig. 1c). The bony sections were obtained via CT scanning of the specimens.

The muscle/tendon connections in the thumb model are depicted in Fig. 1b. The ADPo muscle in the current model is considered to be equivalent to the ADD (adductor pollicis) muscle in the normative model (An et al., 1979), while the ADPt muscle in the current model was not included in the normative model. The ADPo and ADPt tendons have variable wide-flat cross sectional areas and are attached onto the bony sections via a narrow flat region rather than on a point. In the AnyBody modeling system, the tendons are considered as strings with "negligible cross sectional areas". It is clear that the ADPt and ADPo tendons cannot be adequately represented using a single string. In the current study, the ADPt and ADPo tendons are modeled using two strings. The ADPt tendon strings are attached to one point on the proximal bony section and to two points at the trapezium bone, as shown in Fig. 1b. The tendon excursion in the ADPt or ADPo tendon was evaluated using the averaged excursions of two tendon strings.

The length of the proximal phalanx is considered to be 40 mm, and the lengths of the metacarpal bone and the distal phalanx are scaled according to the normative model (An et al., 1979). The predicted muscle/tendon excursions and moment arms were compared with the experimental data by Smutz et al. (1998). Initially, the attachment locations of the tendons from the normative model (An et al., 1979) were applied. The attachment locations were then manually adjusted individually and iteratively for the model predictions to best match the muscle moment arms measured experimentally by Smutz et al. (1998). The excursions of each individual muscle were first calculated from the model. The moment arms of the muscles corresponding to a particular joint were obtained by differentiating the excursions with respect to the corresponding joint rotation. The sign convention is defined consistently for IP, MP and CMC joints, i.e., extension(−)/flexion(+) and abduction(−)/adduction(+).

Table 1
The locations of the tendon attachment used in the current simulations.

Joint	Tendon	Distal point			Proximal point		
		X	*Y*	*Z*	*X*	*Y*	*Z*
IP	EPL	−0.020	0.082	−0.097	−0.150	0.061	−0.044
	FPL	−0.007	−0.150	0.009	0.100	−0.208	0.034
MP	EPL	−0.040	0.125	−0.057	0.125	0.147	−0.084
	FPL	−0.062	−0.150	0.009	0.100	−0.321	−0.012
	ADPt	−0.062	−0.104	−0.040	0.200	−0.150	−0.050
	ADPo	−0.062	−0.104	−0.10	0.0100	−0.175	−0.046
	EPB	−0.050	0.065	0.027	−0.250	0.148	−0.019
	FPB	−0.062	−0.094	0.075	0.100	−0.316	0.095
	APB	−0.062	0.007	0.128	0.100	−0.120	0.253
CMC	EPL	−0.067	0.179	−0.185	0.050	0.180	−0.176
	FPL	−0.067	−0.476	−0.030	0.100	−0.282	−0.030
	EPB	0.067	0.232	0.029	0.050	0.284	0.082
	FPB	−0.067	−0.451	−0.184	0.100	−0.254	0.198
	APL	−0.067	−0.070	−0.148	0.100	0.133	0.180
	OPP	−0.067	−0.136	0.190	0.100	−0.293	0.074
	APB	−0.067	−0.076	0.212	0.100	−0.076	0.309
	ADPt_1	–	–	–	−0.300	−0.636	−0.700
	ADPt_2	–	–	–	−0.100	−0.636	−0.100
	ADPo	−0.067	−0.469	−0.195	0.100	−0.469	−0.300

The attachment locations are defined in the local coordinate on each phalangeal section (Fig. 1); and the values of the coordinates are normalized to the section length of the proximal phalange (O_2O_3, as shown in Fig. 1), according to the normative model (An et al., 1979).

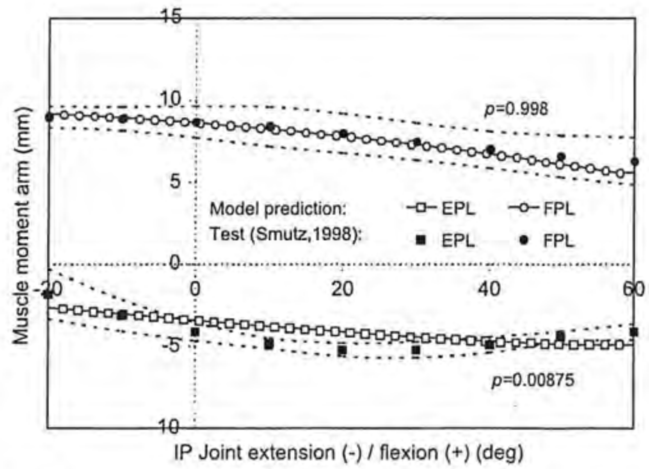

Fig. 2. The comparison of the predicted moment arms of EPL and FPL muscles as a function of the IP extension(−)/flexion(+) with the corresponding experimental data by Smutz et al. (1998). The means and 95% confidence intervals (dotted lines) of the experimental measurements are shown in the figure.

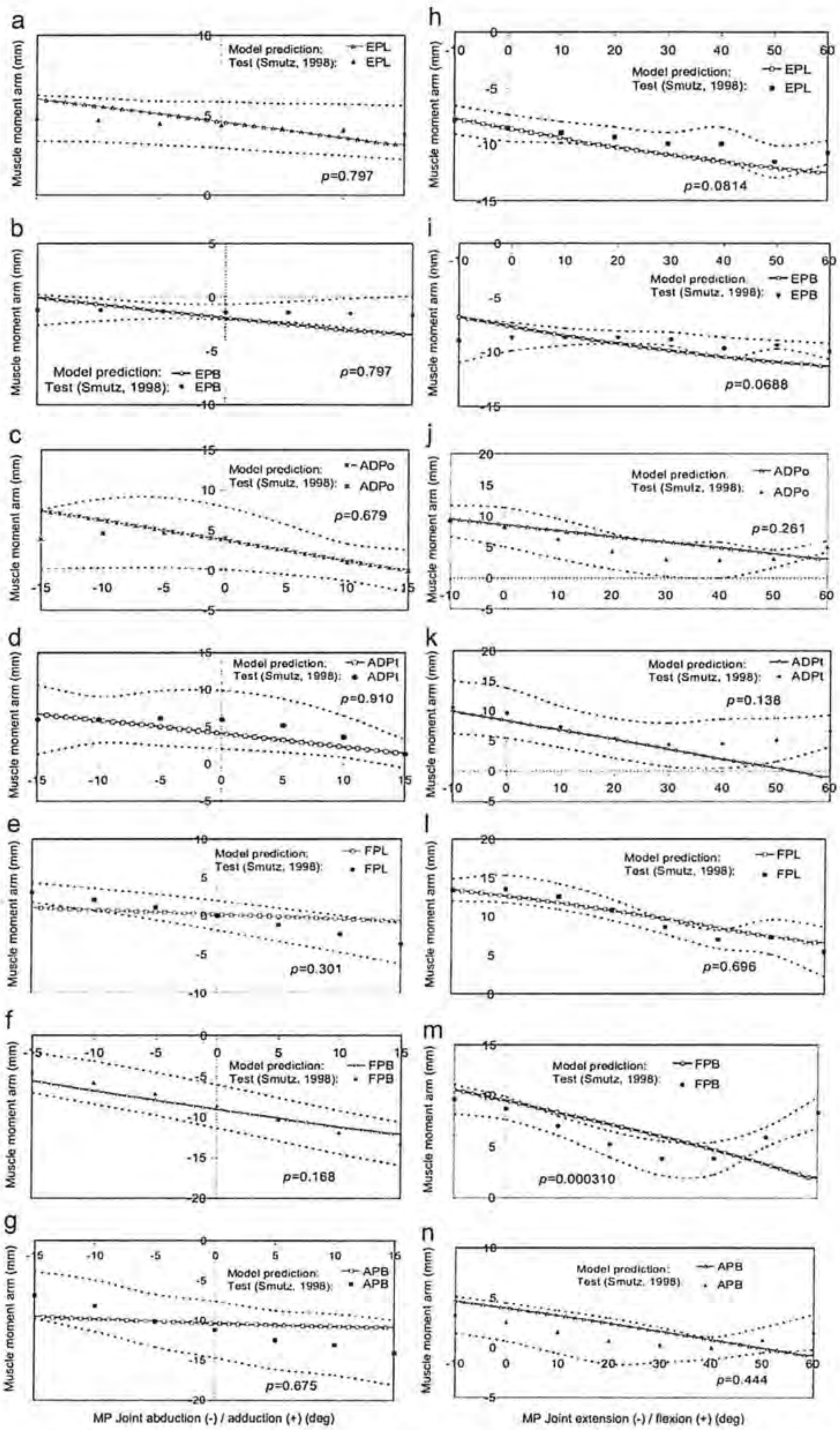

Fig. 3. The comparison of the predicted muscle/tendon moment arms as a function of the MP joint motion with the corresponding experimental data by Smutz et al. (1998). The left column (a–g) of the figures show the moment arms of EPL, EPB, ADPo, ADPt, FPL, FPB and APB muscles as a function of MP abduction(−)/adduction(+). The right column (h–n) of the figures show the moment arms of EPL, EPB, ADPo, ADPt, FPL, FPB and APB muscles as a function of MP extension(−)/flexion(+). The means and 95% confidence intervals (dotted lines) of the experimental measurements are shown in the figures.

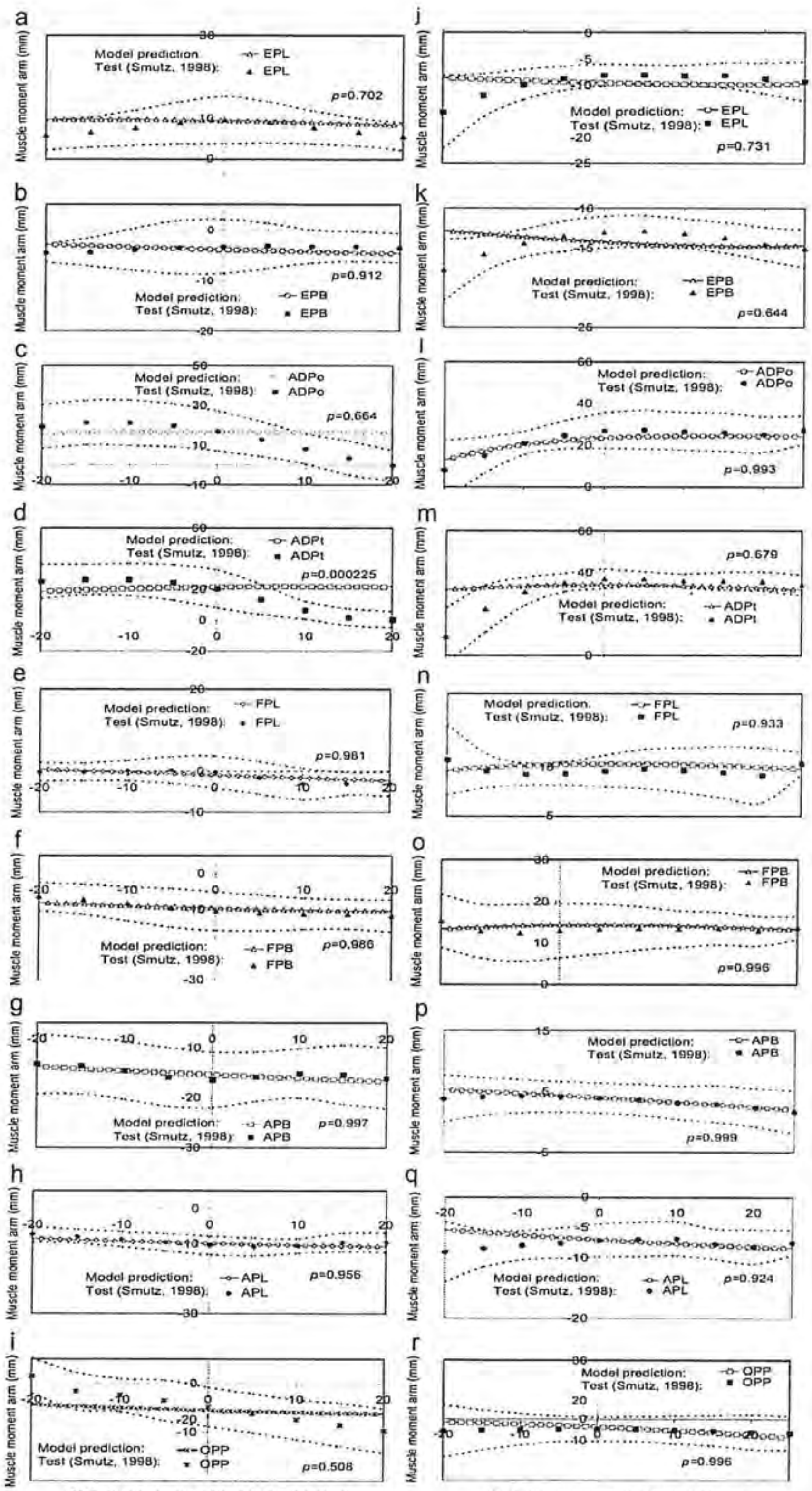

Fig. 4. The comparison of the predicted muscle/tendon moment arms as a function of the CMC joint motion with the corresponding experimental data by Smutz et al. (1998). The left column (a–i) of the figures show the moment arms of EPL, EPB, ADPo, ADPt, FPL, FPB, APB, APL and OPP muscles as a function of CMC abduction(−)/adduction(+). The right column (h–n) of the figures show the moment arms of EPL, EPB, ADPo, ADPt, FPL, FPB, APB, APL and OPP muscles as a function of CMC extension(−)/flexion(+). The means and 95% confidence intervals (dotted lines) of the experimental measurements are shown in the figure.

The tendon attachment locations applied in the current model are listed in Table 1; they are defined in the local coordinate system on each phalangeal section (Fig. 1).

The theoretical predictions are compared with the experimental data (Smutz et al., 1998) graphically in Figs. 2–4, in which the means and 95% confidence intervals of the test data are plotted. The goodness of the agreement between the model predictions and experimental data are evaluated using a reduced Chi-square analysis. The *p*-values of the Chi-square analysis are indicated in the figures. The number of parameters used in the Chi-square analysis was assumed to be 2, 4 and 4 for IP, MP and CMC joint motions, respectively. A *p*-value $\leqslant 0.05$ would indicate a lack-of-fit.

3. Results

The predicted moment arms of the muscles EPL and FPL corresponding to the IP extension/flexion are generally within or close to the regions of the 95% confidence intervals of the experimental data by Smutz et al. (1998) (Fig. 2).

The moment arms of the muscles/tendons with respect to the MP joint motions predicted using the current model are compared with those measured experimentally by Smutz et al. (1998) (Fig. 3). The left column of the figure (Fig. 3a–g) shows the muscle/tendon moment arms corresponding to MP abduction/adduction, while those corresponding to MP extension/flexion are shown in the right column (Fig. 3h–n). Seven muscles (i.e., EPL, FPL, ADPo, ADPt, EPB, FPB and APB) are active in response to the MP joint motions. The model predictions are generally within or close to the regions of the 95% confidence intervals of the experimental data. Only at two instances (i.e., Fig. 3k and m), the predicted moment arms of ADPt and FPB muscles deviate from the corresponding experimental data close to the end of the motion range od MP flexion.

The moment arms of the muscles/tendons with respect to the CMC joint motions predicted using the current model are compared with those measured experimentally by Smutz et al. (1998) in Fig. 4. Similar to the previous figure, the left column of the figure (Fig. 4a–i) shows the muscle/tendon moment arms corresponding to CMC abduction/adduction, while the right column (Fig. 4j–r) shows those corresponding to CMC extension/flexion. All nine muscles in the thumb (i.e., EPL, FPL, ADPo, ADPt, EPB, FPB, APB, OPP and APL) are active during the CMC joint motions. Again, the model predictions agree generally well with the experimental data with exception of two instances (i.e., Fig. 4c and d), in which the predicted moment arms of ADPt and ADPo deviate from the experimental data towards the end of the motion range of CMC adduction.

A statistical analysis indicated that the model predictions agree generally well with the experimental data in most cases (p-value > 0.05). Only in three instances (i.e., Figs. 2, 3m and 4d), the *p*-values for the Chi-square analysis are less than 0.05.

Using the data presented in Figs. 3 and 4, we constructed the diagrams of the moment potentials for the MP and CMC joints, as depicted in Fig. 5a and b, respectively. The moment potential of a muscle is defined as the product of the moment arm of the muscle at the neutral position and its maximal isometric force. The maximal isometric forces represents the maximal forces that muscles can generate and they are evaluated by using the physiological cross-sectional areas (PCSA) (Linscheid et al., 1991; Brand et al., 1981) multiplied by a muscle strength factor of 35.5 N/cm^2 (Epstein and Herzog, 1998). Our results (Fig. 5) show that, except for the ADPt muscle, the theoretically predicted moment potentials agree well with the corresponding data by Smutz et al. (1998).

4. Discussion and conclusion

A comparison of the theoretical predictions with the experimental data indicated that the model predictions agree generally well with the experimental data in the middle of the motion ranges, while close to the end of the motion range the predicted muscle moment arms of the ADPt, ADPo and FPB muscles (e.g., Figs. 3k and m and 4c and d) deviate from the experimental data. The adductor pollicis muscles, especially ADPt, have a large PCSA and are attached to the metacarpal bone and proximal phalanx in a flat-region rather than at a point; and they are modeled using two strings in the current model. The difference between the thumb anatomy and model representations may contribute to the difference between experimental data and the theoretical predictions.

It is noted that in an instance (Fig. 2) the predicted muscle moment arm of EPL for IP joint motion agrees fairly well with the experimental data graphically, while the *p*-value reflects "lack-of-fit" ($p = 0.00875$). This is caused by the exceptionally small values of the standard deviation of the reported experimental data (Smutz et al., 1998). In order to demonstrate the sensitivity of the results, we have recalculated the *p*-value using the standard deviation of the first data point, which seems at a more reasonable level, and obtained a *p*-value greater than 0.969. Since the measurement errors of the muscle excursions for EPL should be comparable to those for all other muscles, the exceptionally small values of the standard deviation for EPL (Fig. 2) were likely a mistake in the original publication (Smutz et al., 1998).

In the current study, the bony linkage in the IP joint is modeled using the hinge while that in the MP and CMC joints are modeled

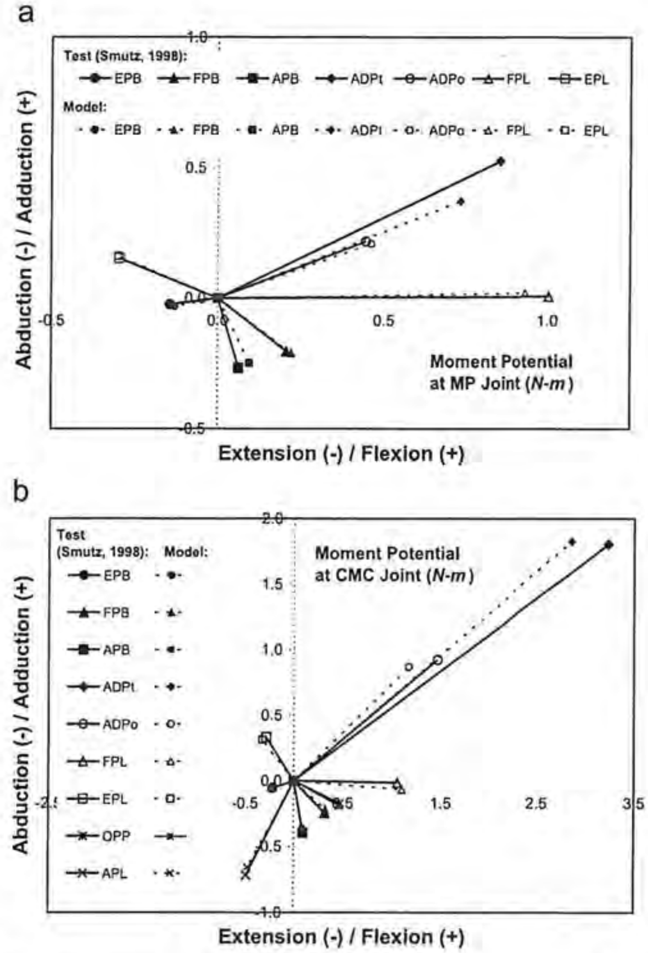

Fig. 5. The comparison of the predicted muscle/tendon moment potentials with the experimental data by Smutz et al. (1998). (a) MP joint and (b) CMC joint.

using the universal joint. In real joints, however, the centers of the joint moment are moving during locomotion, i.e., the joints are sliding and rolling, especially in the MP and CMC joints. In a limited range of motion, the articular joints should be well represented using "mechanical" joints (i.e., hinge or universal joint), as in our model. This may be an other factor that attributed to the differences between the model predictions and experimental measurements towards to the end of the motion range.

Conflict of interest statement

I understand that all authors of this manuscript have no conflict of interest.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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