Journal of Biomechanics 42 (2009) 383–388

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

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

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ARTICLE INFO

Article history:
Accepted 10 November 2008

Keywords:
Thumb
Kinematics
Muscle–tendon excursion
Moment arm
Simulations

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.

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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0021-9290/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.jbiomech.2008.11.008

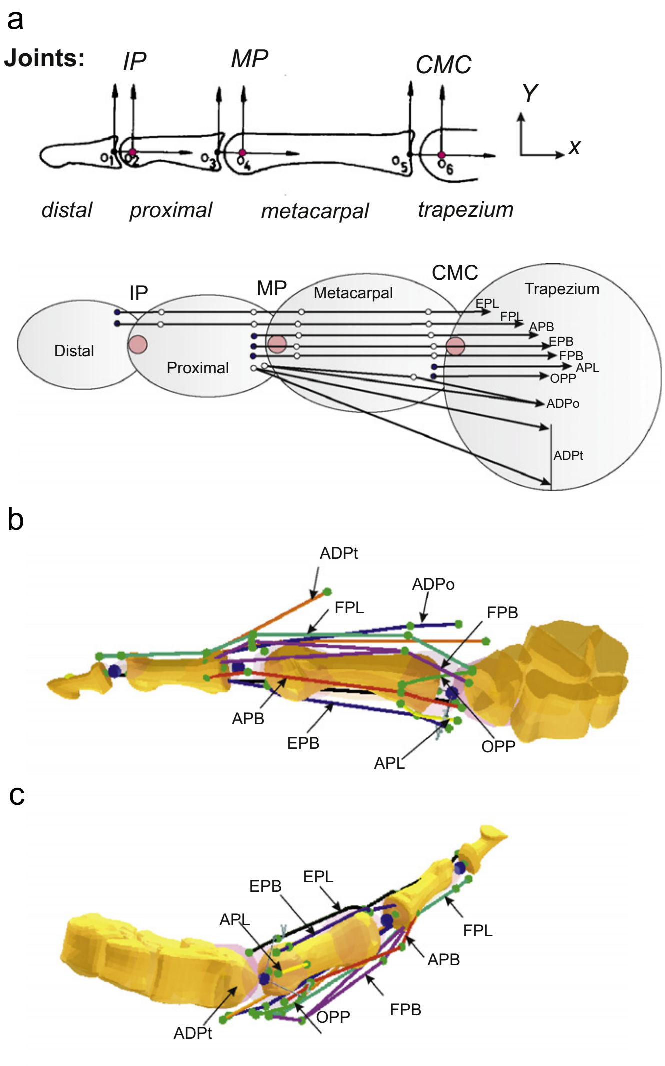

Fig. 1. Schematics of the proposed thumb model. (a) Definition of the coordinate systems in each bony section. (b) Schematics of the tendon network in the thumb model. The solid circles represent the tendon inserting locations, while the hollow circles represent the tendon pulley locations. (c) Schematics 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).

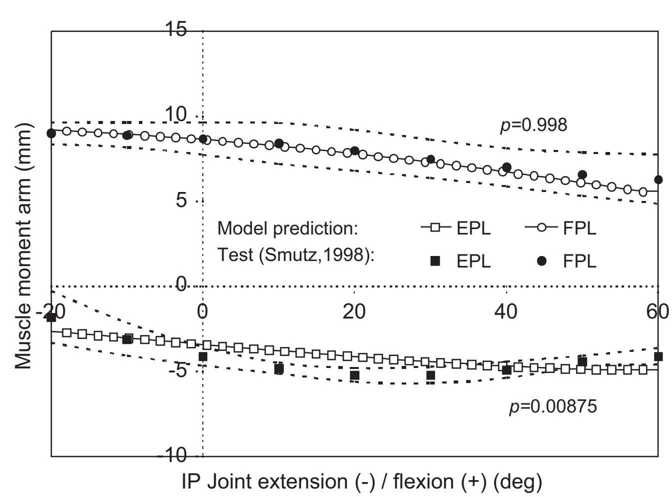

Fig. 2. The comparison of the predicted moment arms of EPL and FPL muscles as a function of the IP extension(−)/flexion(+) with the corresponding experimental data by Smutz et al. (1998). The means and 95% confidence intervals (dotted lines) of the experimental measurements are shown in the figure.