THUMB KINEMATICS WITH NON-ORTHOGONAL AND NON-INTERSECTING AXES OF ROTATION MAY BE NECESSARY TO PREDICT REALISTIC ISOMETRIC THUMBTIP FORCES IN MULTIPLE DIRECTIONS

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INTRODUCTION

Manipulation depends on the thumb's ability to produce well-directed forces of sufficient magnitude. We currently lack a model of the thumb that can realistically predict thumbtip forces in 3D, and the coordination patterns that produce them (Valero-Cuevas, et al., 2003). This may be because the assumed *model structure* is not able to reproduce functional outputs, and/or because the search for adequate *model parameter values* has been unsuccessful. Understanding the inherent biomechanical abilities of a chosen *model structure* is a necessary first step to modeling the thumb for clinical use and studies of neural control of the hand.

METHODS

We investigated whether: (1) adjusting the 50 musculoskeletal parameters (e.g., moment arms, hinge location and orientation) of a five-hinge serial linkage *model structure* (Fig. 1) can predict maximal, voluntary, isometric thumbtip forces measured experimentally; and (2) inputting the measured fine-wire electromyogram (EMG) data into these models produces well-directed forces (within 16° of the desired direction). Using a Bayesian approach that considers model parameters as random quantities instead of single unique values, we found the range of all possible functional outcomes for a specific *model structure* resulting from the natural anatomical variability of the thumb.

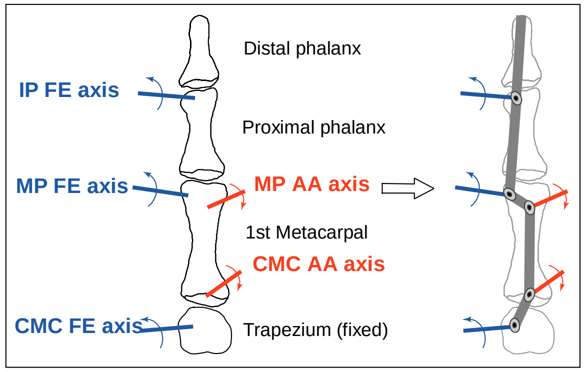

Figure 1: Thumb kinematics modeled as a serial chain of five hinges (Giurintano, et al., 1995). (*CMC=carpometacarpal, MP=metacarpo-phalangeal, IP=interphalangeal*)

We used a Markov Chain Monte Carlo (MCMC) algorithm to explore this 50-D parameter space (Gilks, et al., 1996). We represented each parameter by a statistical distribution based on published or measured data (Santos, et al., 2003). The MCMC algorithm stochastically explored the *model parameter space* using 10 independent Markov chains to find the model parameter distributions that drove input/output predictions towards a least-squares fit to thumbtip force/torque measurements. Chain convergence was determined by the Gelman-Rubin statistic (Gilks, et al., 1996), which indicates when all chains can be pooled for drawing inferences. Converged chains were extended such that 20,000 pooled iterations were achieved.

The exploration was driven by an "inverse" linear programming (LP) solution predicting maximal biomechanically feasible thumbtip forces. For a given thumb posture, static force production reduces to a matrix multiplication (Valero-Cuevas, et al., 2003), making LP appropriate for predicting the limits of performance. We then performed "forward" simulations using fine-wire EMG measurements, instead of inverse LP solutions, to evaluate the input-to-output behavior of the models.

RESULTS AND DISCUSSION

The distributions of parameter values to which all chains converged are those that can produce well-directed thumbtip forces in 3D for this robotics-based model structure. Since MCMC methods perform an exhaustive search of the *parameter* space (Gilks, et al., 1996) there is *no other* sub-region in the 50-D parameter space that would fit the measured force data better. Our MCMC approach has the important benefit of rigorously predicting the functional consequences of natural anatomical variability of the thumb.

We found model-predicted maximal thumbtip forces to be lower than those measured (Table 1), but closer to the measurements compared to the predictions of a simpler kinematic model with mutually orthogonal and intersecting axes of rotation at the CMC and MP joints (Valero-Cuevas, et al., 2003). The five-hinge serial linkage model predicted maximal palmar forces comparable to those predicted by the simpler model and improved upon predictions in the dorsal and distal directions for both pinch postures.

Table 1: Comparison of thumbtip force magnitudes between experimental measurements (n=4) and model predictions (20,080 pooled iterations). We observe improvements in model predictions over those from a simpler kinematic model (Valero-Cuevas, et al., 2003) in the dorsal and distal force directions for both pinch postures.

Pinch-type	Force dir.	Expt.		Model		Expt:Model Mean ratio
		Mean	Std	Mean	Std	
Key	Palmar	54.4	26.0	14.0	7.4	3.9
	Dorsal	10.7	3.0	9.0	1.9	1.2
	Distal	58.2	32.3	96.1	10.7	0.6
	Radial	21.5	9.7	5.7	3.1	3.8
	Ulnar	16.9	2.9	2.2	1.2	7.7
Opposition	Palmar	46.3	34.9	11.1	4.7	4.2
	Dorsal	10.8	3.2	7.2	2.6	1.5
	Distal	54.3	43.5	25.2	13.6	2.2
	Radial	22.2	8.3	8.1	2.8	2.8
	Ulnar	25.8	13.5	1.8	1.4	14.0

However, it is reasonable to consider increasing the PCSA values (collected from elderly cadavers) to better approximate the forces produced by the young subjects. For the forward simulations, we inputted the measured EMGs into the models resulting from the inverse MCMC simulations and found that thumbtip forces were not well directed. We will now pursue the question of whether EMG-based MCMC simulations can lead to more realistic models, or if non-hinged kinematic model structures of articular surface mechanics must be considered for future modeling.

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