STOCHASTIC ANALYSIS OF ANATOMICAL DATA SUGGESTS THREE CHARACTERISTIC TYPES OF THUMB KINEMATICS

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INTRODUCTION

From the most precise pinch to the most powerful grasp, the versatility and utility of the human thumb is evident whenever we use our hands to interact with objects. A detailed analysis of the kinematics and dynamics of the thumb is important to understand the effects of orthopedic and neurological diseases, and to design and evaluate rehabilitative and surgical treatments.

Our work has shown that simply assuming a kinematic description of the thumb that has intersecting and orthogonal axes of rotation at the carpometacarpal (CMC) and metacarpophalangeal (MP) joints cannot predict realistic thumbtip forces [1]. Therefore, it is necessary to increase the complexity of the kinematic description to create realistic models of the thumb.

Giurintano *et al.* [2] proposed a five degree-of-freedom (DOF), virtual five-link model of the thumb, and measured its parameters in cadaver thumbs [3,4]. The links are "virtual" in that they correspond to the distance between effective hinges, and not simply the three long bones of the thumb, as in previous models. Adjacent virtual links are connected to one another by one hinge. The CMC and MP joints each have two axes of rotation, one for flexion-extension (FE) and one for adduction-abduction (AA). The interphalangeal (IP) joint has one axis of rotation for flexion-extension. However, this kinematic description is not available in a standard format amenable for use in robotics-based models. Moreover, it is not known how the reported large variability of the anatomical data [3,4], which may be informative of kinematic differences among individuals, affects the kinematic descriptions of the thumb. Simply using the mean axis location and orientation values may not be representative of any one individual.

The virtual five-link model differs from its predecessors in that the FE and AA axes are not orthogonal to one another or to the long axes of the bones, and adjacent axes do not necessarily intersect one another within the bones of the thumb. The versatility of the Denavit-Hartenberg (DH) representation of robotic joints makes it the logical choice to describe the complex virtual five-link manipulator for the construction of the forward kinematic equations of the thumb such that rigorous robotics analyses may be applied.

The objective of this work was twofold: to use the cadaver data describing this virtual five-link model to create a kinematic description in standard robotic notation to facilitate its inclusion in robotics-based models, and to estimate the effect of the reported anatomical parameter variability on the kinematic description of the thumb.

METHODS

The location and orientation of each axis of rotation were measured experimentally using cadaver thumbs and an "axis finder" and then presented in the literature as two-dimensional projections [3,4]. We used these projections to create the transformation matrices necessary to achieve the three-dimensional orientation of each axis. This required a conversion of the given projection angles into spherical coordinates such that the transformation could be broken down into two rotations and one translation.

Once the transformation matrices had been calculated for all five axes of rotation and the axes had been visualized in Mathematica®, the DH representation of the axes was determined. The four DH parameters (θ, d, a, α), which describe the location and orientation of subsequent local joint reference frames, were calculated for each pair of adjacent joints [5].

Since a range of values was reported for the location and orientation of the axes of rotation, it was necessary to calculate a range of values for each of the DH parameters using Monte Carlo simulations, one type of stochastic analysis technique. For each Monte Carlo simulation, a pseudo-random set of anatomical and axis location/orientation parameters was selected from uniform distributions bounded by reported mean values ± one standard deviation [1,3,4]. The DH parameters were then determined for each random set of parameters. We considered 3,000 simulations to be sufficient for the convergence of the DH parameter estimates because their mean and coefficient of variance changed by less than 1% for the last 20% of the simulations.

RESULTS

Unimodal, bimodal, and trimodal distributions were observed in some DH parameters despite the initial uniform distributions of the anatomical parameters. Three characteristic sets of DH parameters were found as per the relative locations of the metacarpophalangeal FE and AA axes. In 64.4% of the simulations (sets 1 and 2), the MP FE axis was distal to the MP AA axis. In 35.6% of the simulations (set 3), this order was reversed. The MP FE axis was slightly dorsal to the IP FE axis in set 1 (30.6% of the simulations) and slightly palmar to the IP FE axis in set 2 (33.8% of the simulations). Figure 1 depicts one representative instantiation of the virtual five-link model of the thumb from set 1.

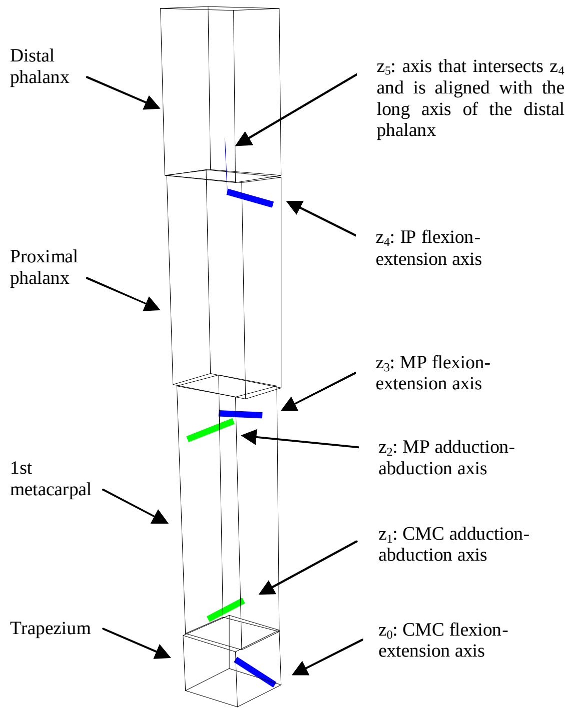

Figure 1. Representative instantiation of the five axes of rotation, depicted by the bold lines, for set 1. (Not to scale)

	Frame #				
DH param.	1	2	3	4	5
a (cm)	1.21 (0.26)	3.22 (0.74)	0.38 (0.27)	0.11 (0.08) *0.11 (0.08)* **3.96 (0.37)**	0 (0)
d (cm)	-0.25 (0.26)	3.31 (2.20) *3.31 (2.20)* **0.71 (0.77)**	-3.02 (2.09) *-3.02 (2.09)* **0.62 (0.36)**	14.54 (3.79) *14.54 (3.79)* **-0.92 (0.41)**	-14.35 (3.87) *-14.35 (3.87)* **-0.76 (0.22)**
α (rad)	-1.40 (0.13)	-0.58 (0.15) *-0.58 (0.15)* **1.35 (0.13)**	1.87 (0.08) *1.87 (0.08)* **-1.87 (0.08)**	-0.31 (0.07) *0.32 (0.07)* **1.82 (0.08)**	1.69 (0.04)

Table 1. Three characteristic sets of Denavit-Hartenberg parameters, shown with mean (std). Where necessary, three different sets of values are specified with set #2 values in italics and set #3 values in bold. The θ values are not specified since they are rotational DOF's.

DISCUSSION

Reversal of the metacarpophalangeal FE and AA axis order was expected from the wide range of MP axis parameters in [3,4]. However, we had no reason to expect that there would be that many more cases in which the FE axis was distal to the AA axis. Understanding the kinematic differences between the two different cases of relative MP axis locations could be critical to the design of surgical techniques and the success of the clinical outcomes.

The large standard deviations in DH parameter distributions reflect the relatively large standard deviations in the reported anatomical data (possibly due to small sample size and/or actual anatomical variability [3,4]). Since we lack published relationships among kinematic parameters of the thumb, our Monte Carlo simulations did not set any parameter covariances. Thus, we likely included some unrealistic combinations of parameters that may have further increased the standard deviations of our results. Since anthropometric data were not reported for the data we used [3,4], we do not know if factors such as subject sex, hand size, or anatomical variability contributed to the trends observed in the Monte Carlo simulations, or if the three characteristic sets of DH parameters are associated with these factors.

By converting the two-dimensional projections of the axes of rotations into DH parameters, this work has provided a description of the thumb as a manipulator using roboticist conventions. This allows the complex kinematics of the thumb and its functionality to be analyzed using a rigorous robotics approach. For instance, the DH parameters can easily be used as input to robotics-based programs to calculate quality metrics such as manipulability ellipsoids and grasp stability.

Future improvements to this kinematic model of the thumb involve the addition of non-rotational degrees of freedom. Pearlman *et. al.* [6] found that the trapezium, routinely assumed to be the fixed base of the thumb, subsides under load. Thus, a truly realistic kinematic model of the thumb may need to include a trapezium with load-dependent translational DOF's. Additional improvements include the use of contact theory to model the kinematics of arbitrarily-shaped articulating bone surfaces at the CMC joint, for example.

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