

MOMENT-GENERATING CAPACITY OF TENDONS IN FINGER MOVEMENTS: EVALUATION OF THE TENDON MOMENT ARMS OBTAINED FROM THE EXCURSION METHOD

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INTRODUCTION

A tendon moment arm, defined as the distance between the joint center and the tendon line of action, is generally used to assess the moment-generating capacity of the muscle-tendon unit around the joint. Excursion method that utilizes the relationship between the tendon excursion and the joint rotation (An et al., 1983) has been commonly employed to estimate the moment arm values. In the human finger, however, some tendons generate the rotation of the segments into which they do not have insertions; for example, the flexor digitorum profundus (FDP) tendon is involved in generating flexion or extension of the proximal phalanx (PP), into which they do not have apparent insertions. Instead, the rotation of the PP is generated via the joint reaction forces, transmitted from the distal segments into which the tendon inserts, or pulley forces that constrain the tendon paths. It is thus unclear if the tendon moment arm values obtained from the excursion method can be employed to estimate the joint moment produced via such mechanisms.

In this study, we examined if the moment arms of the finger tendons estimated by the excursion method can represent their moment-generating capacity in hand movements. We utilized two different models of the finger, one employing the moment arm values from the excursion method, and the other considering more realistic joint moment generation mechanisms (via joint reaction forces and pulley forces). The spatial and temporal coordination of the multi-joint

flexions obtained from the two models were examined and compared for this purpose.

METHODS

Two types of the dynamic models of the index finger were developed. The first model (model 1) employed the moment arm values of the tendons obtained from the excursion method (An et al., 1983) in order to estimate the joint moments generated by the tendon forces, whereas the second model (model 2) estimated the joint moment magnitudes directly from the force and moment balance equations considering the pulling forces at insertions, subsequent joint reaction forces, and the forces acting on the pulley structures.

In both models, the index finger was represented as an open chain of three rigid segments connected through three one degree-of-freedom (DOF) joints. The abduction (or adduction) of the MCP joint was not considered in the model, since the flexion or extension of the three joints were mainly examined and little abduction/adduction is generated by FDP or FDS tendons. The finger segments are represented as conical cylinders with density of $1.1(\text{g}/\text{cm}^3)$, and the dimensions of finger segments were acquired from the literature (An et al., 1979; An et al., 1983). Passive stiffness and damping values at each joint obtained from Kamper et al. (2002) were also incorporated in the models. In the model 1, the joint moment magnitude generated at each joint in response to the tendon force application was estimated by directly

multiplying its moment arm value to the tendon force. In contrast, the second model (model 2) calculated the joint moments by incorporating the force and moment equilibrium equations at all three joints. Here, three types of moment generating mechanisms were considered: 1) the direct tendon pulling forces from the insertions (\mathbf{b}_T), 2) the joint reaction forces that transmit the tendon forces from the adjacent segments (\mathbf{b}_R), 3) the forces acting on the tendon pulleys constraining tendon path (\mathbf{b}_P) (Roloff et al., 2006), 4) passive stiffness and damping (\mathbf{b}_S), and 5) Coriolis force (\mathbf{b}_C) term (Eq. 1).

$$\mathbf{I}\ddot{\boldsymbol{\theta}} = \mathbf{b}_c(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \mathbf{b}_r(\boldsymbol{\theta}, \mathbf{f}_t) + \mathbf{b}_R(\boldsymbol{\theta}, \mathbf{f}_t) + \mathbf{b}_p(\boldsymbol{\theta}, \mathbf{f}_t) + \mathbf{b}_s(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) \quad (1)$$

(\mathbf{I} : inertia matrix, $\boldsymbol{\theta}$: joint angle vector)

Tendon forces of FDP = 4 (N) and FDS = 3.2 (N) were applied. Forward dynamic simulations for both models were performed using the 4th-order Runge-Kutta method in MATLAB (MathWorks, Inc. Natick, MA).

RESULTS AND DISCUSSION

Noticeably different joint flexion patterns were produced by two models (Fig. 1). The model 1, adopting the moment arm values from the excursion method, resulted in larger flexion angle in the MCP joint ($>90^\circ$) than PIP joint, whereas the PIP joint flexion angle was greater than the MCP flexion in the movement generated by the model 2. Similar movement patterns were observed in the different FDP/FDS force combinations. Both models were capable of producing realistic sigmoidal angular profiles and inter-joint temporal coordination pattern (Holguin et al., 1999).

Note that the joint flexion patterns generated by the electrical stimulation of the FDP/FDS muscles (Kamper et al., 2002) were more comparable to the movement obtained from the model 2 (PIP>MCP). Similar joint flexion patterns were also reported in Long and Brown (1964), in which the electromyography confirmed that the FDP and FDS were the main muscles for generating such movements.

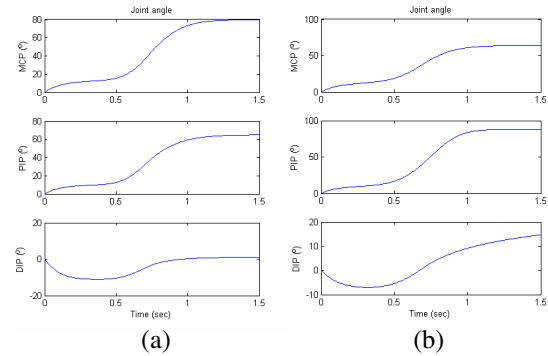


Figure 1. Joint angles simulated by two models (a) model 1: MCP>PIP>DIP (b) model 2: PIP>MCP>DIP

We also examined the contribution of different elements to the angular acceleration of each joint, i.e. from the tendon pulling forces ($\mathbf{I}^{-1}\mathbf{b}_T$), joint reaction forces and tendon pulley forces ($\mathbf{I}^{-1}(\mathbf{b}_R + \mathbf{b}_P)$), passive stiffness/damping ($\mathbf{I}^{-1}\mathbf{b}_S$), and the Coriolis force $\mathbf{I}^{-1}\mathbf{b}_C$, in the model 2 (Fig. 2). Here, \mathbf{b}_P and \mathbf{b}_R are specifically found to be functionally important in most joints.

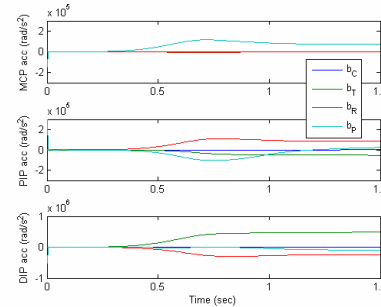


Figure 2. Contribution of different elements to the joint angular acceleration

The results of this study indicate that the excursion method can overestimate the moment generating capability of some tendons, specifically when the tendon is not directly inserted into the segment. Also, the analysis of different elements (Fig. 2) suggests that factors other than direct tendon pulling force should be carefully considered in analyzing the dynamics of the finger movement generation.

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