A PROBABILISTC BIODYNAMIC MODEL FOR FINGER TENDON FORCE ESTIMATION CLARIFIES THE ROLES OF THE FLEXORS

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INTRODUCTION

Previous deterministic finger biomechanical models predicted that the flexor digitorum superficialis (FDS) was silent whereas the flexor digitorum profundus (FDP) was the only active flexor during finger flexions [1-2]. Experimental studies in vivo, however, recorded activities of both flexors [3-5]. This study proposes a probabilistic biodynamic model for estimating the muscle-tendon forces in the index finger during flexion. Our hypothesis is that accommodating variability of musculoskeletal parameters in a model will result in better population-based predictions of the muscle-tendon forces, and specifically will clarify the roles of the flexors (FDP and FDS) in finger movement.

METHODS

The index finger is modeled as a 3-segment and 4-DOF linkage system actuated by 11 muscle-tendon units with flexion/extension at distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints and zero abduction/adduction angle at its MCP joint. This system is subject to the moment equilibrium condition, $\tau(t) = M(t)\cdot F(t) + \tau_{passive}(t)$, where *F(t)* is the muscle-tendon force, *M(t)* represents the moment arms of these forces, and $\tau_{passive}(t)$ is the passive torque. The $\tau_{passive}(t)$ is assumed effective only for MCP flexion/extension and follows a polynomial torque-angle relationship $a_3\theta^3 + a_2\theta^2 + a_1\theta + a_0$ [7], where a_3, a_2, a_1, and a_0, are the coefficients of the polynomial and θ is the joint angle. The force constraints reflecting the interconnected nature of multiple finger tendons [1] are included in the model. The muscle-tendon forces can be estimated by solving a nonlinear optimization problem with the objective function of minimizing the muscle stress, defined as the quotient of the muscle force divided by its physiological cross sectional area (PCSA). Force predictions by the above dynamic model depend on model parameters including moment arms, PCSAs, and passive torques.

In previous deterministic models, moment arms of extensors and PCSA values are assumed constant across subjects for the entire range of motion (Figure 1a); moment arms of flexors and passive torques are assumed constant across subjects for a given posture (Figure 1b).

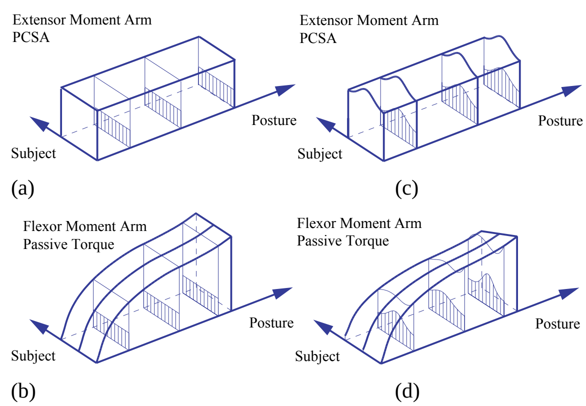

Figure 1. Uniform, posture-independent (a) and posture-dependent (b) distributions of parameters commonly used in deterministic models; more realistic posture-independent (c) and posture-dependent (d) distributions in the proposed model.

The current model recognizes the variability in these parameters and models them as random variables using Monte-Carlo methods (Figure 1 c,d) as follows. The moment arms *m* of the flexors and extensor tendons (ES: extensor slip and TE: terminal tensor) are estimated as $m = r$ for extensors, and $m = d + y \cdot g(\theta)$ for flexors [6], where *d* is the distance between long axis of the bone and the tendon, *y* is the distance from the joint center to sheath, $g(\theta)$ is a function of θ. We model the *r, d, y* parameters as well as the PCSA values of the two flexors, and the four coefficients of passive torque, a_3, a_2, a_1, and a_0, as independent random variables following a normal distribution. The means of these parameters are from [1,6,7] and the variances of the parameters are chosen to be one-tenth of the means. The length and thickness of each segment are also modeled as the random variables with the mean and standard deviation derived from a pre-established database [8]. Two thousand samples are generated for each of the random variables and served as the input to the biodynamical model described above. Parameters of other muscle-tendon units in this model are calculated based on the methods from [1]. The proposed probabilistic model is tested on an experimentally measured index finger movement from a pre-established database [8]. Identical joint kinematic data are used in all instantiations of the simulation.

RESULTS AND DISCUSSION

The predicted flexor forces (Figure 2) display a pattern that qualitatively agrees with what was recorded in an in-vivo study [5]. The predicted FDP force declines in the initial phase of the movement (the first 0.4s) and then increases to sustain the motion and dominated the movement after the initial phase. The FDS dominates the movement in the initial phase and decreases significantly before the FDP dominates the movement. This FDS force-time pattern in the initial phase also agrees with previous observations [3]. An inspection of the individual flexor force profiles reveals that another type of force pattern reported in [5] could be simulated. Both the FDP and FDS forces formgamma distributions at a given time or posture (Figure 3). When the FDP dominates the movement, the FDS is no longer silent (Figure 2). The probability for FDS not being silent (FDS force >0. 01N) ranged from 36.4%~56.7%.

CONCLUSIONS

We demonstrated that the proposed model was able to unveil the active, intricate roles of the FDP and FDS during finger flexion, which previous deterministic models failed to show [1-3]. The results clarified the controversy surrounding the roles of the flexors in finger movement dynamics and demonstrated the efficacy of probabilistic models in predicting more realistic muscle-tendon forces for a population.

Compared to previous stochastic biomechanical modeling work [9,10], this study features a novel method to incorporate both the inter-person and movement-dependent variabilities of musculo-skeletal parameter. Capturing these variabilities is critical for the implementation of stochasticity in dynamical modeling. Previous models have neglected the fact that the moment arms are not only subject-specific but also posture-dependent. Such an oversimplification may only be adequate for static biomechanical modeling.

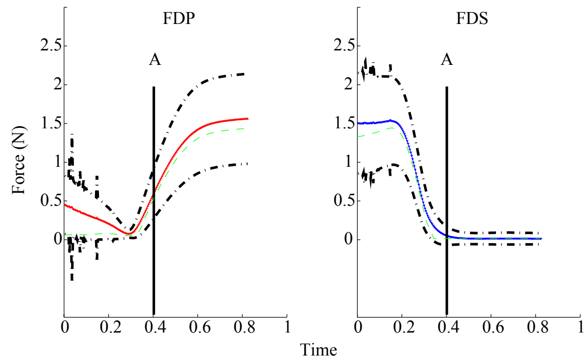

Figure. 2. The predicted FDP and FDS force distributions during the movement: the time-varying mean (solid line) and ±1 standard deviation (between the two dash-dot lines). The vertical solid lines denote the time point before which the FDS dominated the movement and after which the FDP dominated the movement. The dashed line is the force profile predicted by a deterministic model.

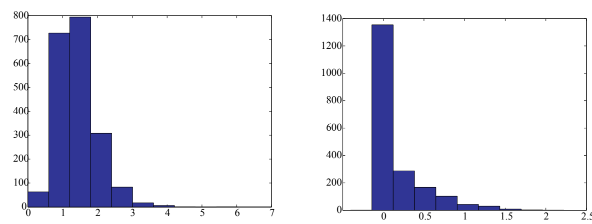

Figure. 3. The FDP and FDS force distributions at a randomly selected posture when the FDP was the major flexor.

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