DYNAMIC MODELING AND SYSTEM IDENTIFICATION OF FINGER MOVEMENT

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INTRODUCTION

Biomechanical models for hand movement can aid in various industrial design and clinical evaluation processes. There exist kinematic models for grip posture prediction [1, 2] and inverse dynamic models for estimating muscle forces in static poses or movements [3, 4]. However, a forward dynamic model of finger movement, particularly one that is empirically based and computationally efficient, has been lacking.

This study aims to develop a dynamic model for predicting human finger movements during manipulative actions. The model incorporates a control scheme modulating dynamic stiffness and damping of the fingers to generate desired movements, and parametric system identification allowing empirical estimation of the parameters characterizing the dynamic properties.

METHODS

The database for model development was from an experiment in which an anthropometrically diverse group of 28 subjects performed grasping motion tasks. Joint angular profiles derived were found to be of sigmoidal shape, which were then represented compactly by parametric hyperbolic tangent functions [4]. A constrained non-linear optimization was formulated to determine the parameter values of hyperbolic tangent functions best fitting the joint angular profiles.

A proportional-derivative (PD) control scheme was proposed to govern the system dynamics. The torque at joint i (i=1, 2, 3) was computed as:

$$T_i = -K_i^p\left(\theta_i - \theta_i^f\right) - K_i^d\left(\dot{\theta}_i - \dot{\theta}_i^f\right), \quad T_i \le M_i^{max} \qquad (1)$$

where θ_i denotes the angle of joint i, θ_i^f the joint angle in terminal posture, K_i^p the proportional feedback gain, K_i^d the derivative feedback gain, and M_i^{max} the upper limit of torque value generated at joint i. K^p and K^d characterize two main movement-specific properties: dynamic joint stiffness and damping. M^{max} corresponds to the torque maximum, i.e., the peak value of torque profile. In forward solutions given the parameter values, the 4th-order Runge Kutta method was employed.

The controller parameters were estimated in an optimization routine that minimized the discrepancy between the model-predicted and measured movement profiles. The discrepancy was represented as the difference between two sets of profile attributes: response time, peak velocity, and peak acceleration. These attributes are in fact the parameters in the aforementioned hyperbolic tangent functions fitting the measured profiles. The optimization routine iteratively estimated the control parameters resulting in model response that best matched the measurement. It should be noted that the movement speed affects the parameter values (e.g., faster movement requires greater feedback gain and torque values). To remove the effect of speed, the obtained control parameters were normalized using a linear regression model. This parameter estimation scheme was applied to the movement database to determine the speed-scaled K^p, K^d and M^{max} values.

RESULTS AND DISCUSSION

The mean and standard deviation values of K^p and M^{max} are shown in Figure 1. K^d values showed a similar pattern across the digits as K^p (means for digit 2 to 5 were 6.9, 6.4, 6.1 and 2.5 × 10^{-3} N s m/rad, respectively). The grand mean RMSE (SD) value for 336 model-reproduced joint angular profiles was 4.88° (3.75°).

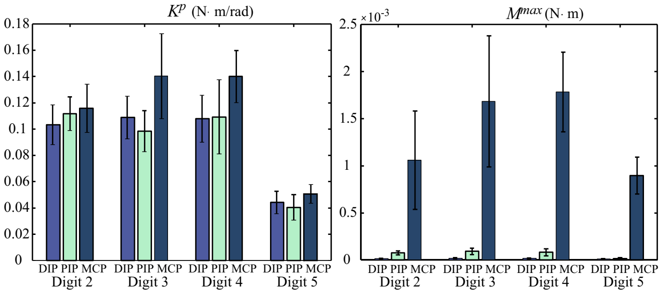

Figure 1: Mean and SD of estimated K^p and M^{max} values.

Estimated active joint stiffness K^p values were in a comparable range for digits 2 to 4, but were considerably smaller for digit 5. This can be considered as a reflection of the difference in anthropometric properties. A similar pattern was exhibited by K^d values. The K^p and K^d values for MCP were slightly greater than those for DIP and PIP, while the M^{max} values of the MCP joints were 10-100 times greater. These results are consistent with the understanding that most physical work in grasping motion is done by MCP flexion. They also are corroborated by an invasive EMG study [5] that discovered significantly higher levels of muscle activation associated with MCP flexion during grasping motions.

The proposed model enables computationally efficient and physically interpretable prediction of finger movement, owing to the simple control and parametric system identification scheme. Potential applications include computer-aided design of hand-operated products, clinical diagnosis of hand-related disorders or impairment.

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