A COMPREHENSIVE EXPERIMENTAL EVALUATION OF EXISTING MODELS OF THE EXTENSOR MECHANISM CALLS FOR NOVEL DATA-DRIVEN MODELS

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INTRODUCTION

The functional role of the components of the extensor mechanism to finger function has been debated for decades. While several computational models have been suggested over the years, the normative model developed by An et al. 1979 [1] remains the most comprehensive 3D anatomical model of the index finger to date. Though this model has been used in multiple studies (Eg. [2]), it has not been rigorously validated with experimental data. The model assumes simple bowstringing of all tendons with joint rotation, and a constant force distribution within the different bands of the extensor mechanism (i.e., independent of joint posture). Both assumptions are contrary to experimental observations. Valero-Cuevas et al. in 1998 [4] emphasized the importance of including changes in force distribution through the extensor mechanism with finger posture. They modified a constant moment arm model proposed by An et al, 1983 [3] to include changes in force distribution through the extensor mechanism with posture. However, neither of these models has been validated with experimental data consisting of force transmissions from tendons to the fingertip. In this paper, we evaluate the normative model of the index finger as well as the constant moment arm models described in An et al, 1983 and Valero-Cuevas et al. 1998, with experimental data collected from a cadaveric index finger in multiple postures.

METHODS

We actuated the seven tendons of the index finger (*flexor digitorum profundus* (FDP), *flexor digitorum superficialis* (FDS), *extensor indicis* (EI), *extensor digitorum communis* (EDC), *first lumbrical* (LUM), *first dorsal interosseous* (FDI), and *first palmar interosseous* (FPI)) of a fresh-frozen cadaveric hand using dc motors controlled by a National Instruments PXI real-time control system (Fig. 1). All possible combinations of 'low' (2N) and 'high' (10N) tendon tensions were applied to the cadaveric specimen at random while we recorded the corresponding fingertip forces and torques using a 6 DOF load cell attached to the fingertip. This procedure was repeated at three different postures, P1 (fully flexed), P2 (tap) and P3 (extended).

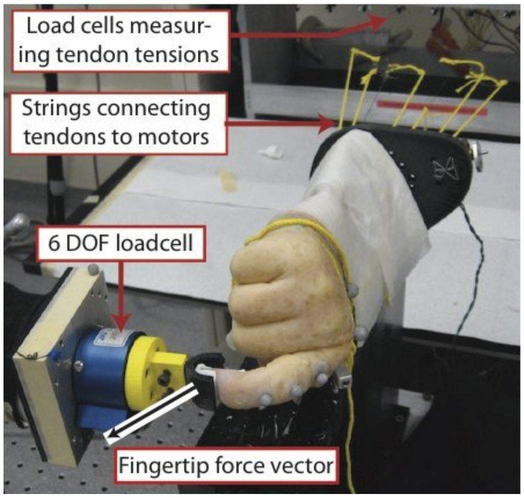

Figure.1 Experimental setup used to collect fingertip force data from cadaveric specimens.

The experimental action matrix transforming tendon tensions to fingertip forces was regressed in each posture (mean R^2 =0.99). This experimental action matrix was compared against the matrices predicted for those same postures by each of the three models. For the An et al. 1979 model, the moment arm matrix at each finger posture was calculated in MATLAB as described in [1] and using equations for force distribution through the extensor mechanism described in [5]. The action matrix was calculated by multiplying the inverse transpose of the Jacobian, with the moment arm matrix [4]. Similar action matrices were determined for the An et al, 1983 and Valero-Cuevas et al., 1998 models.

All moment arm matrices were scaled to the length of the middle phalanx to reduce the effect of inter-subject variability [1]. Each column of the action matrix (an action vector) represents the fingertip force resulting from 1N tension applied to the corresponding tendon. The robustness of the models to variations in moment arm values was also tested by applying ±10% uniformly distributed noise to the moment arm matrices in the three models.

RESULTS AND DISCUSSION

Fig. 2 shows the changes in magnitude and direction of each tendon's action vector as the finger shifts from fully flexed (P1) to a more extended posture (P3). The changes for all models and experimental data (in black) are relative to P1. In general, the magnitude changes in the three models disagree with the experimental data, and amongst themselves in several important cases. The changes in direction for tendons other than EI and EDC (sagittal plane) and LUM, FDI and FPI (radio-ulnar plane) also do not match with corresponding changes in experimental data. The directional errors for the EI and EDC in the radio-ulnar plane can be neglected because the components of their action vectors in this plane are small.

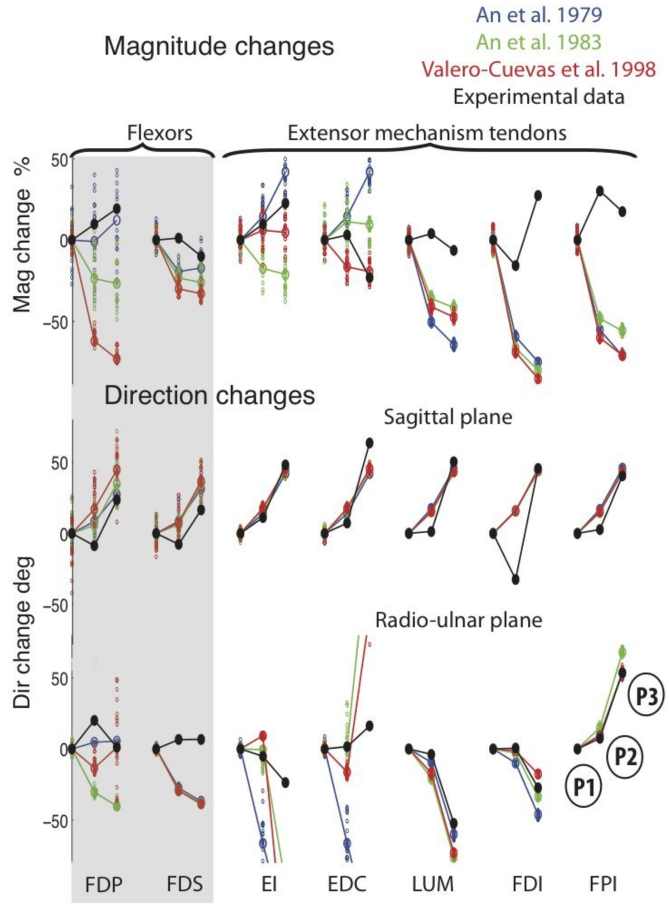

Figure. 2. Comparison of magnitude and direction changes of fingertip force vector resulting from 1N tendon tension in models and experimental data as the finger shifts from a fully flexed (P1) to a more extended posture (P3).

Perturbing the moment arms of the three models by ±10% demonstrates that they can be extremely sensitive to parameter values; especially the flexors (FDP and FDS) and the extensors (EDC, EI that are important contributors to the extensor mechanism), which see 30°-40° change in fingertip force direction and ~50% change in magnitude. This lack of robustness is a major flaw of models to predict finger mechanics, and calls for better data-driven subject-specific finger models.

CONCLUSIONS

Our experimental evaluation of the existing models of the index finger reveal that, in general, they do not capture the physics of the system and are functionally inaccurate. More detailed and accurate representations of the topology and parameters of the extensor mechanism, inferred from experimental data, are necessary to develop reliable biomechanical models to understand motor control of manipulation and changes upon damage.

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