Current Biomechanical Models of the Index Finger Fail to Predict Experimental Observations

[1]Manish U. Kurse, [2]Hod Lipson and [1,3] Francisco J. Valero-Cuevas
[1]Department of Biomedical Engineering, University of Southern California, Los Angeles, CA
[2]Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY
[3] Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA

Abstract:
Existing computational models of the human fingers are simplistic and do not capture the physics of interactions of the different components of the extensor mechanism. These models, though widely used in the literature to model finger mechanics have not been validated with experimental data. In this paper, we rigorously validate three index finger biomechanical models : the normative model developed by An et al., 1979 and two constant moment arm models presented by An et al. 1983 and Valero-Cuevas et al. 1998, respectively. We compare fingertip forces predicted using these models with forces measured experimentally in a human cadaveric index finger. We observe that while the predictions of all models deviate largely from experimental measurements, fingertip force errors are larger for the extrinsic extensors and the intrinics, tendons that insert into the complex extensor mechanism. We conclude that these errors could be due to inaccuate and incomplete representations of the extensor mechanism in these models.

Introduction:
The role of the different components of the extensor mechanism in finger function has been long debated in the literature. While several simplistic 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 employed in several research studies (Eg. [2]), it has never been rigorously validated with experimental data. The model assumes bowstringing of all tendons with joint rotation and a constant force distribution within the different bands of the extensor mechanism, independent of joint posture. Both the above assumptions are modeling simplifications and 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], obtained by regression of tendon excursion-joint angle data from cadaveric specimens, to include changes in force distribution through the extensor mechanism with posture. But the validity of fingertip force predictions of neither of these models has been tested with experimental data. In this paper, we rigorously validate 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:
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), in a freshly frozen cadaveric hand were actuated 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 and corresponding fingertip forces and torques were recorded

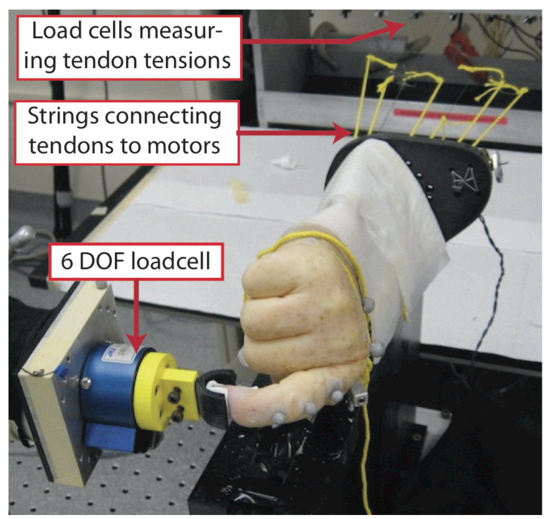

Fig.1 Experimental setup used to collect fingertip force data from cadaveric specimens.

using a 6 DOF load cell attached to the fingertip. This procedure was repeated at four different postures in one cadaveric specimen.

A matrix transforming tendon tensions to fingertip forces (which we shall call the action matrix) was regressed from the experimental data in each posture (mean R^2 =0.96). The normative model of the index finger was implemented in MATLAB. The moment arm matrix corresponding to each finger posture was calculated based on rotations of tendon positions 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 mapping joint angle velocities to fingertip velocities, with the moment arm matrix [4]. Similar action matrices were determined for the constant moment arm models of An et al, 1983 and Valero-Cuevas et al., 1998. Fingertip force predictions were obtained by multiplying these action matrices with tendon tensions. All moment arm matrices were scaled to the length of the middle phalanx to reduce the influence of subject variability [1].

Results:
The fingertip force vector predicted by each finger model upon application of 1N tension on a single tendon was compared to that generated by the action matrix regressed from experimental data. This was repeated separately for each tendon and for all postures. The magnitude error in Fig 2 is defined as the difference in fingertip force magnitudes for the simulated model and experimental data and the direction error is the angle between the simulated and experimentally observed force vectors.

The fingertip force predictions of all models differed largely from experimental measurements for all tendons. Large variations exist even across the different models. The errors for the extrinsic extensors and intrinsics, tendons inserting into the extensor mechanism, were larger than those for the flexors for all models (except the Valero-Cuevas model for FDP).

Discussion:
Larger errors for finger extensors and intrinsic muscles compared to finger flexors could be attributed to an inaccurate representation of the extensor mechanism in these models. Including deformations of the extensor mechanism with finger posture and the resulting changes in force distribution may lead to more accurate biomechanical finger models [4]. While some of the error could be due to measurement noise and subject-to-subject variability, magnitude errors > 100% and directional errors > 30 degrees are larger than what these sources of error would produce. More detailed and accurate representations of the topology and parameters of the extensor mechanism are necessary to develop reliable biomechanical models of the finger that can then be used to understand motor control of manipulation and changes upon damage.

References:

[1] KN An, EY Chao, WP lii Cooney, RL Linscheid, Normative model of human hand for biomechanical analysis, *Journal of Biomechanics (1979)*, 12, 775-788

[2] DC Harding, DK Brandt, BM Hillberry, Finger joint force minimization in pianists using optimization techniques, *Journal of Biomechanics (1993),* 26(12), 1403-1412.

[3] KN An, Y Ueba, EY Chao, WP lii Cooney, RL Linscheid, Tendon excursion and moment arm of index finger muscles, *Journal of Biomechanics (1983),* 16 (6), 419-425.

[4] FJ Valero-Cuevas, FE Zajac, CG Burgar, Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. *Journal of Biomechanics (1998), 31(8), 693-703,*

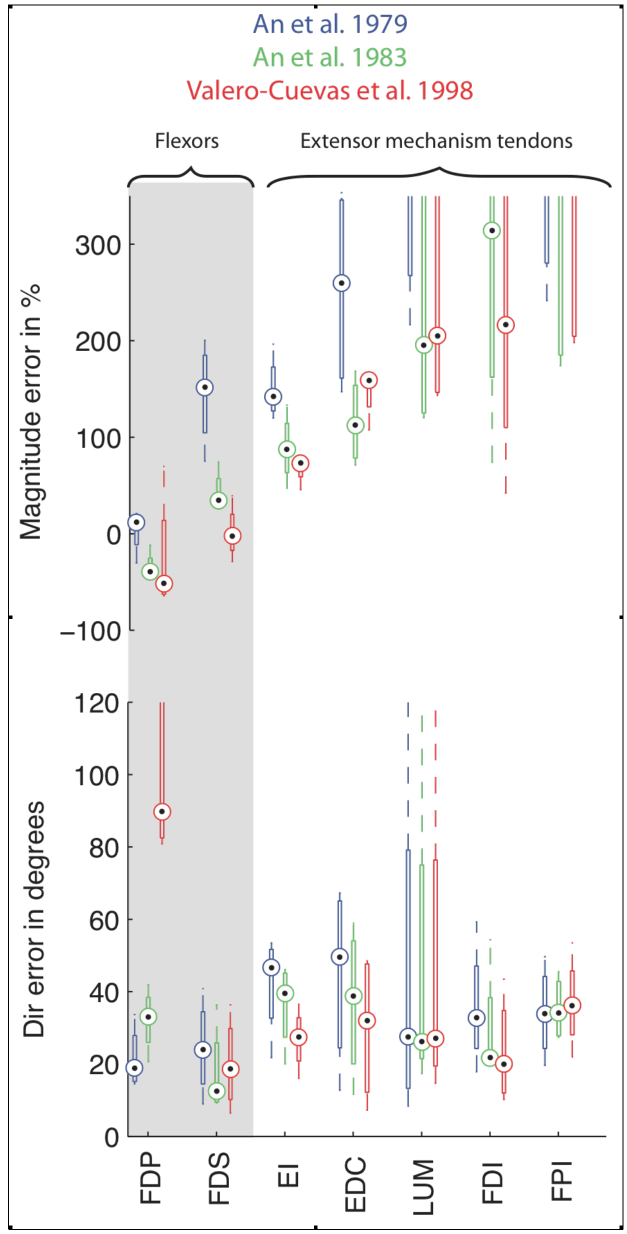

Fig. 2. Box plots showing errors in magnitude and direction of fingertip force vectors predicted by three models of the index finger when 1N tendon tension was applied to the respective tendons. The black circles represent median values.

Acknowledgments:
This material is based upon work supported by NSF Grants EFRI-COPN 0836042 and NIH Grants AR050520 and AR052345 to FVC.