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DEVELOPMENT OF BIOMECHANICAL INDEX FINGER MODEL TO PREDICT MULTI-SEGMENTAL GRIP FORCES FOR VARYING FINGER POSTURES

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INTRODUCTION

Motivation and Significance

- Hand injuries account for 1/3 of all injuries at work [1].
- Many hand injuries occur when a task requires hand strength exceeding one's capability.
- To reduce these injuries, optimal design of objects to maximize the hand's physical strength via biomechanical modeling is needed.
- However, current literature provides maximum strength data only empirically for limited shapes and sizes of handles.

Objective

- To develop a novel biomechanical index finger model which can predict the maximal grip strength across all phalanges during handle grasping with varying shapes and sizes

METHODS

Inclusion of Pulley Mechanism

- Instead of using a fixed moment arm length, a moment arm length as a function of joint angles and muscles was used.
- Five pulleys (A1, A2, A3, A4, and A5) were added to the model.
- Geometrical information of each pulley was obtained from [2] (Fig. 1).
- Interaction forces between tendon and pulley were added (Fig. 2).

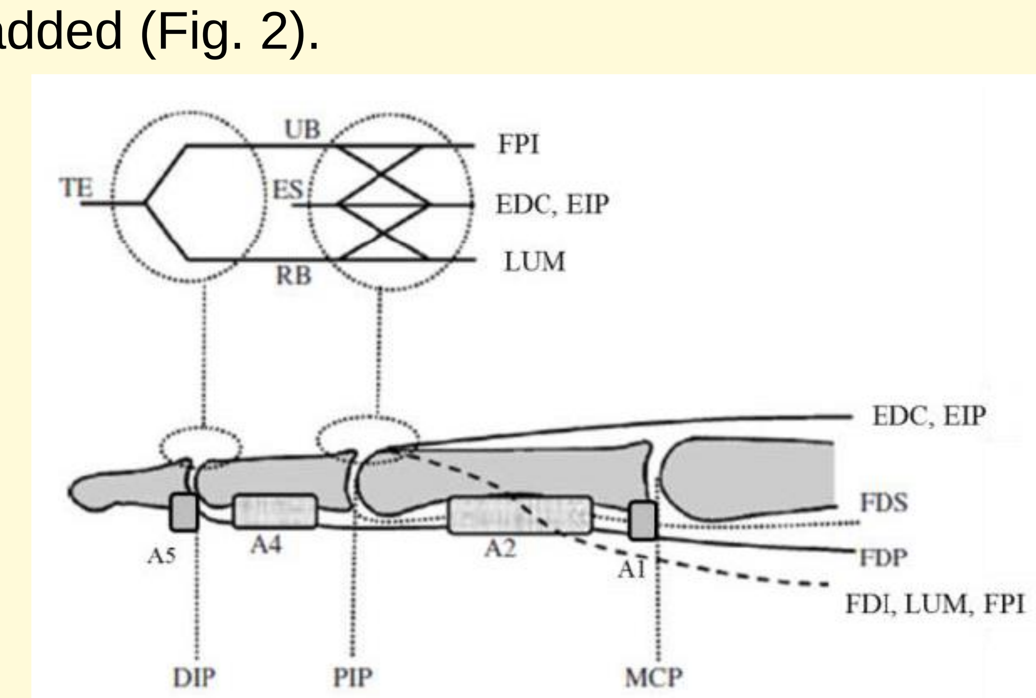

Fig. 1: Tendons and pulleys for the index fingers act on the multiple finger joints and segments. The extensor mechanism connects the tendons for FPI, EDC, EIP and LUM to the extensor bands.

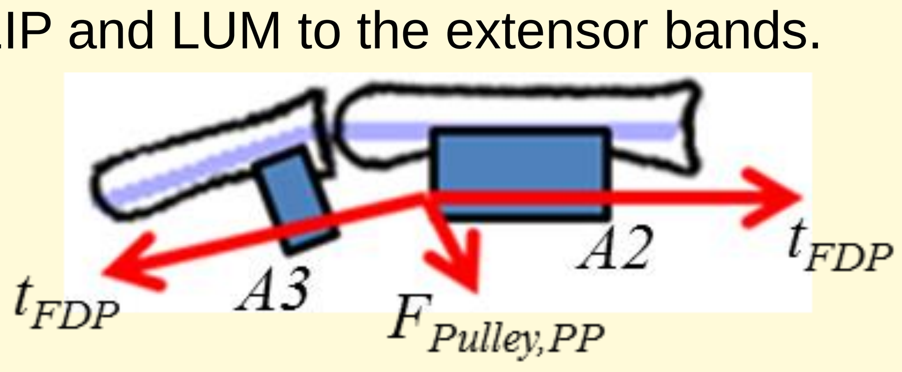

Fig. 2: Tendon-pulley interaction produces additional forces at each phalanx

Inclusion of Passive Properties at Joints

- Passive joint torque at each joint due to the contribution of passive tissues such as ligaments, skin and joint capsules were considered [3].

Inclusion of Extensor Mechanism

- Extensor mechanism was included in the model to consider the complicated networks of tendons for extension of a finger (Fig. 1).
- Extensor tensions are linear combinations of several muscles. Some of the coefficients depend on finger postures and will be found by optimization [4].

Consideration of Force-Length Relationship for Muscles and Tendons

(Please ask the author for the detailed derivation of equations)

- Depending on finger posture, muscle fiber length changes, which affects the maximum force a muscle can generate [5] (Fig. 3a).

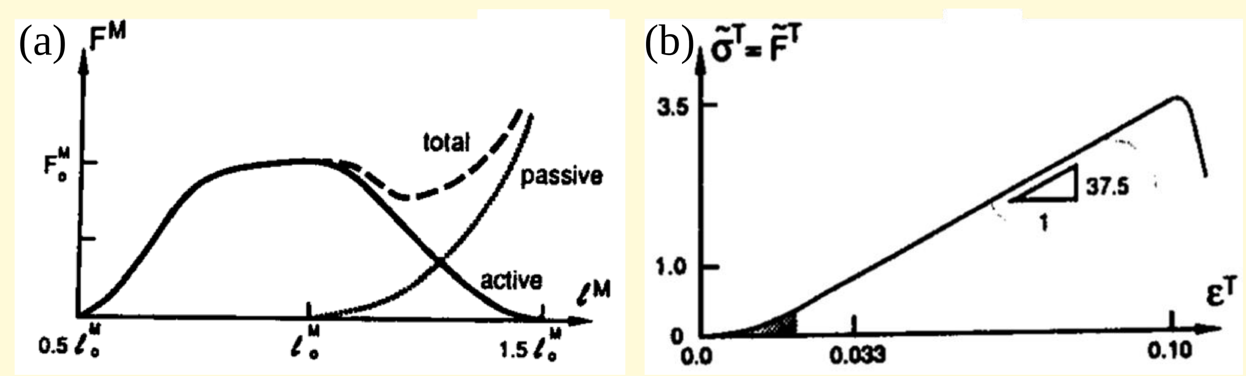

Fig. 3: (a) Force-length relationship for a muscle and (b) stress-strain curve for a tendon [5].

- Optimal muscle fiber lengths (L_o^M) were obtained from [6] and rescaled to have the optimal sarcomere length of 2.64 µm [7].
- Strain (ε^T) of tendon will have the following relation

$$\varepsilon^T = \begin{cases} \dfrac{\tilde{L}^{MT} - \tilde{L}^M}{\tilde{L}_s^T} - 1 & if\ \Delta\tilde{L}^T > 0 \\ 0 & otherwise \end{cases}$$

where L^{MT} is muscle tendon length, L^M is muscle fiber length, L_s^T is tendon slack length and L^T is tendon length. For a given finger posture, L^{MT} is known. ~ means that the variable is normalized by the optimal muscle fiber length (L_o^M).

- Then, the following stress information can be computed.

$$\sigma^T = s\left(\varepsilon^T\right) = \sigma^P + \sigma^A$$

where s(·) is a function that maps strain to stress in Fig. 3b, σ^P and σ^A are passive and active stresses of a muscle. σ^P can be found from Fig. 3a and σ^A will be found during optimization.

Two-Level Optimization

- *Inner-level optimization*: to find the muscle fiber length ($\tilde{L}^M$) to maximize the external contact forces.

$$\text{find } \tilde{L}^M \text{ for all muscles, and } \alpha_{FPI}, \alpha_{LUM}, \alpha_{EDC+EIP}$$
$$\max f_{ext}^{DP} + f_{ext}^{MP} + f_{ext}^{PP}$$
$$\text{subject to}$$
$$f_{ext}^{DP}, f_{ext}^{MP}, f_{ext}^{PP} \geq 0$$
$$0 \leq \sigma^A \leq f_a\left(\tilde{L}^M\right)$$
$$0 \leq \alpha_{LUM}, \alpha_{FPI} \leq 1$$
$$0 \leq \alpha_{EDC+EIP} \leq 0.5$$

- *Outer-level optimization*: to find the optimal tendon slack length such that the estimated external contact forces best replicate the experimental data in the literature [8].
- Maximum extension angles were 10° and Maximum flexion angles were 90° for all joints.
- Muscle fiber length ($\tilde{L}^M$) was assumed to be within 0.5 and 1.5.

$$\text{find } \tilde{L}_s^T \text{ for all muscles}$$
$$\min \sum_{i,j} \left(f_{ext,\text{ref}}^{i,j} - f_{ext,\text{model}}^{i,j} \right)^2 \qquad i \in \{DP, MP, PP\}, j \in \{5 \text{ handles}\}$$
$$\text{subject to}$$
$$\frac{\max\left(\tilde{L}^{MT}\right) - 1.5}{1.048} \leq \tilde{L}_s^T \leq \min\left(\tilde{L}^{MT}\right) - 0.5 \quad \text{for all muscles}$$

RESULTS AND VALIDATION

- Optimal tendon slack lengths (Table 1) and estimated external contact forces (Fig. 4) to replicate the experimental data are shown below.

Table 1. Normalized tendon slack length from outer-level optimization

	FDP	FDS	FDI	LUM	FPI	EDC	EIP
$\tilde{L}_s^T$	4.00	4.47	1.58	0.67	1.87	5.86	2.91

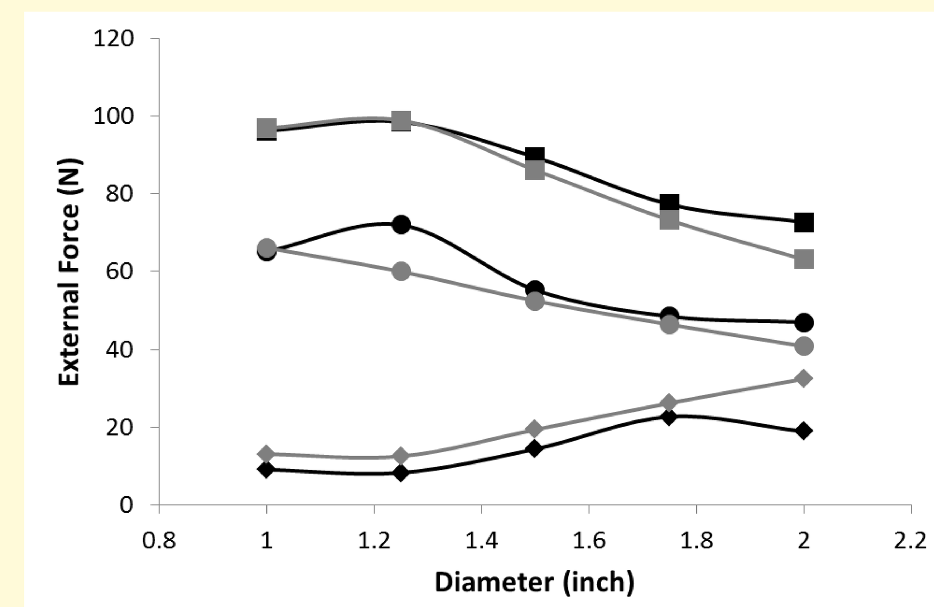

Fig. 4: External forces at each phalanx. Black: reference data in [8]. Grey: estimated forces. ■ Proximal, ● middle, ♦ distal phalanges.

- Additional validation was performed using six handle shapes (Table2).
- Maximum grip strengths from 12 subjects grasping handles were measured with a pressure mat.

Table 2. Validation results

	DIP(°)	PIP(°)	MCP(°)	Σf,exp(N)	Σf,model(N)
Square	35.8	73.7	59.2	113.6	98.2
Tall Rec	49.8	64.9	48.5	113.5	178.9
Wide Rec	40.4	80.9	46.2	70.4	87.2
Circle	38.5	64.6	56.1	103.5	110.0
Tall Oval	53.6	67.5	48.7	180.5	201.6
Wide Oval	42.4	78.6	46.7	65.9	149.5

CONCLUSION

- Maximum grip strengths were estimated with a biomechanical model and optimization.
- Tendon slack lengths were optimized.
- Model predictions deviated from the measured data possibly due to low resolution of pressure mat and different data characteristics between measured data and data from [8].

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