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

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INTRODUCTION

Hand and fingers injuries account for 1/3 of all injuries at work, 1/3 of chronic injuries, 1/4 of lost working time, and 1/5 of permanent disability [1]. Many hand injuries occur when a task requires hand strength exceeding one's capability. To reduce these hand injuries, ergonomists have tried to optimize the design of work objects to maximize the hand's physical capacity via biomechanical analyses.

However, these efforts are primarily empirical, limited to specific shapes and sizes of handles examined. These empirical data are not sufficient to extrapolate and predict grip strengths for a new set of handle shapes and sizes. Currently available hand/finger models are also limited, because they are insensitive to changes in finger posture and predict force only at the fingertip.

Therefore, the objective of this study was to develop a novel biomechanical index finger model which can predict the maximal grip force across all phalanges during grip of objects in varying shapes and sizes.

METHODS

A new index finger model was developed by incorporating the tendon pulley mechanism [2], passive properties of soft tissues [3], and extensor mechanism [4] for the seven muscles controlling the index finger. The novelty of this model is that all above three aspects were taken into account concurrently to predict the maximum grip forces across all phalanges for varying postures.

The distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints were frictionless hinges with one degree of freedom in flexion/extension. The seven muscles for the index finger were: first dorsal interosseous (FDI), first lumbrical (LUM), first palmar interosseous (FPI), flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), extensor digitorum communis (EDC) and extensor indicis proprius (EIP). Four more tendons were included for the extensor mechanism: terminal extensor (TE), extensor slip (ES), radial band (RB) and ulnar band (UB). Finally, 5 annular pulleys (A1 through A5) were included (Fig. 1).

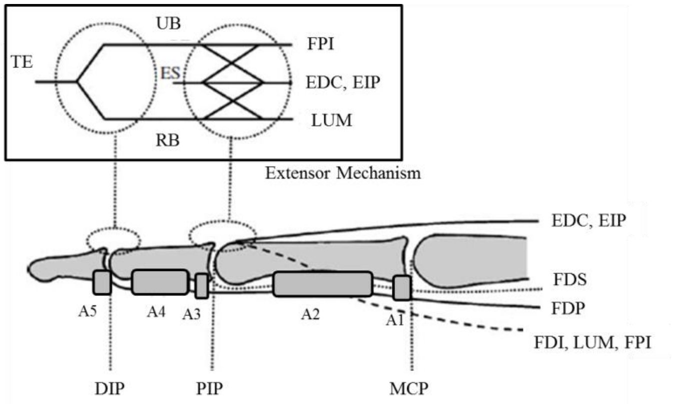


Figure 1: The index finger model with pulleys and the extensor mechanism

The pulley mechanisms defined how muscles' moment arm lengths changed as a function of joint angle. In addition, due to pulleys, tendon tension produced forces not only at the insertion sites, but also at the interaction points with pulleys. For example, FDP inserts at and flexes the distal phalanx (DP). At the same time, FDP influences the middle (MP) and proximal (PP) phalanges due to the interactions with pulleys. The interaction force was computed as a vector sum of the two tendon tensions at each pulley according to their geometric configurations (Fig. 2). All parameter information for pulleys was adopted from [2].

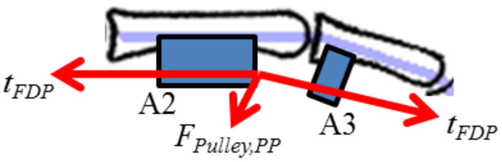


Figure 2: Tendon-pulley interaction force

Passive joint torque at each joint due to the contribution of soft tissues such as ligaments, skin, and joint capsules also changed as a function of joint angle [3] in the model.

The extensor mechanism by Brook [4] was used to model tendon tension distribution in the complicated extensor tendon network depending on the geometric configuration as follows.

$$t_{TE} = 0.992 t_{RB} + 0.995 t_{UB}$$
$$t_{RB} = \alpha_{EDC+EIP} t_{EDC+EIP} + \alpha_{LUM} t_{LUM}$$
$$t_{UB} = \alpha_{EDC+EIP} t_{EDC+EIP} + \alpha_{FPI} t_{FPI}$$
$$t_{ES} = \ 1 - \alpha_{FPI} \ \ t_{FPI} + \ 1 - \alpha_{LUM} \ \ t_{LUM} + \ 1 - 2\alpha_{EDC+EIP} \ \ t_{EDC+EIP}$$

where $\alpha_{EDC+EIP}$, α_{FPI}, and α_{LUM} are the contribution of the corresponding muscle(s) to the four tendon tensions in the extensor mechanism. All tendon tensions except the four (t_{TE}, t_{RB}, t_{UB}, t_{ES}) were limited by the physiological cross-sectional area (PCSA) [5] times the maximum muscle stress (s=35 N/cm^2) [6]. The MP length was assumed 24.5 mm and defined other phalanx lengths proportionally [2].

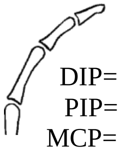
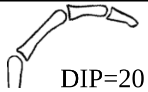
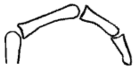
Maximizing external contact forces across all phalanges was the goal of optimization. External contact forces were assumed to be perpendicular to and at the center point of the contacting phalanx. The model and optimization were implemented in MATLAB (v8.0; The MathWorks, Natick, MA).

Find t_i (i=FDP, FDS, LUM, FDI, FPI, EDC+EIP)
$\alpha_{EDC+EIP}$, α_{FPI}, α_{LUM}
Maximize $F_{External,DP} + F_{External,MP} + F_{External,PP}$
Subject to $0 \le t_i \le PCSA \times s$
$0 \le \alpha_{EDC+EIP} \le 0.5$, $0 \le \alpha_{FPI}, \alpha_{LUM} \le 1$
$F_{External,j} \ge 0$
$F_{Tendon,j} + F_{Pulley,j} + F_{External,j} + F_{Joint,j} = 0$
$M_{Tendon,j} + M_{Pulley,j} + M_{External,j} + M_{Joint,j} + M_{Passive,j} = 0$
(j = DP, MP, PP)

RESULTS AND DISCUSSION

The predicted grip strength changed with finger posture as shown in the 3 examples in Table 1. Grip strength increased as the finger closed. Grip strength for DP was the greatest followed by PP and MP. These trends agreed with literature [7].

Table 1. Predicted grip strength for 3 finger postures

Posture / Segment	 DIP=10 ° PIP=25 ° MCP=30 °	 DIP=20 ° PIP=45 ° MCP=45 °	 DIP=20 ° PIP=50 ° MCP=70 °
DP	56.8 N	61.3 N	61.3 N
MP	5.3 N	20.3 N	24.7 N
PP	5.5 N	34.4 N	46.7 N

For future work, the model will be scalable according to user-specific PCSA and hand length. The model validation will be performed by comparing the predictions to measured data. In addition, a user interface will be developed so that ergonomists and industrial designers can apply this new index finger model to improve ergonomics of work objects and consumer products, thereby reducing hand injuries.

CONCLUSIONS

A novel index finger model was developed to predict the maximum grip forces across all phalanges for varying finger postures. This model integrated the 5 pulleys, extensor mechanism, and passive properties. Upon addition of scalability and validation, the model will be made accessible to ergonomists and industrial designers via graphical user interface to enhance ergonomic designs of work objects and reduce hand injuries due to overexertion.

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