

Constructing a Finger Biomechanical Model for Virtual Ergonomic Assessment in Digital Hand

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Abstract— The Digital Hand is a precise and movable 3D model of a human hand and has been developed for virtual ergonomic assessments for product design. In ergonomic assessments, estimating the force of grasping and manipulating the product are effective in constructing reasonable assessment criteria. Therefore, in this paper, we proposed a method to derive internal force distribution of a finger in the Digital Hand software by building a musculoskeletal model, and by solving a non-linear optimization problem on the forces of finger muscle-tendons and the joint surfaces in case of the pinch and the power-grasp. The simulation results were validated by comparing the estimated muscle-tendons forces with the ones of the simulation and experimental results in past literatures.

Keywords— biomechanical model, finger modelling, biomechanics, musculoskeletal model, ergonomics, digital hand, CAD

I. INTRODUCTION

Ergonomic-conscious design of hand-held products, such as electronic appliances, handy tools and containers, contributes a great deal to increasing their high value and market competitiveness. However, current ergonomic assessment of these products, such as comfort or fatigue

estimation of grasps, are still dependant on sensory tests by real human subjects where the manufactures need to prepare expensive mockups but obtain only subjective and qualitative evaluation results.

To solve these problems, our research group has proposed the Digital Hand where the 3D bone structure, surface skin geometry and finger motion of the human hand were precisely modelled. The simulation in the Digital Hand software enables us to generate plausible grasp postures and to predict the quantitative measures of grasp stability [1] and fitness [2] as grasp quality measures. However, internal forces acting on internal finger muscle-tendons during grasping which might strongly relate to the comfort and fatigue of the grasp were not estimated in our previous Digital Hand studies.

Therefore, in this paper, a biomechanical model is developed and introduced into our Digital Hand where the 3D musculoskeletal structure in one finger is modelled and the internal muscle-tendon loads can be estimated. The estimation was reduced to a non-linear optimization problem. Finally, in the pinch and power-grasp postures, the validity of the proposed biomechanical model is discussed by comparing the simulation results obtained from our model with the ones of past simulation and experimental results.

TABLE I
NOMENCLATURE

<i>FDP</i>	Flexor digitorum profundus	$F_{x,n}$	Force vector of x-axis in n th joint
<i>FDS</i>	Flexor digitorum superficialis	$F_{y,n}$	Force vector of y-axis in n th joint
<i>EDC</i>	Extrinsic digitorum superficialis	$M_{xy,n}$	Joint moment of sagittal plane in n th joint
<i>EIP</i>	Extrinsic indicis proprius	$M_{xz,n}$	Joint moment of transverse plane in n th joint
<i>RI</i>	Radial interosseous	$JRF.n.x$	Joint reaction force of n th joint directed along the x-axis
<i>UI</i>	Ulnar interosseous	$JRF.n.y$	Joint reaction force of n th joint directed along the y-axis
<i>LU</i>	lumbrical	F_i	Independent muscle-tendon force variable in i th tendon
<i>LE</i>	Long extensor (index: <i>EDC</i> + <i>EIP</i>)	$\theta_{MP,FE}, \theta_{PIP,FE}, \theta_{DIP,FE}$	Flexion/Extension angle of MP,PIP,DIP joint, respectively
<i>ES</i>	Extensor slip	$\theta_{(MP+PIP),FE}, \theta_{(MP+PIP+DIP),FE}$	Flexion/Extension angle derived by adding $\theta_{MP,FE}$ & $\theta_{PIP,FE}$, $\theta_{MP,FE}$ & $\theta_{PIP,FE}$ & $\theta_{DIP,FE}$, respectively
<i>TE</i>	Terminal extensor	$\theta_{MP,AA}$	Abduction/Adduction angle of MP joint
<i>UB</i>	Ulnar lateral band	$\alpha_{i,FE}$	Correction coefficient of moment arm in i th muscle-tendon at abduction/adduction joint motion
<i>RB</i>	Radial lateral band	$\alpha_{i,AA}$	Correction coefficient of moment arm in i th muscle-tendon at flexion/extension joint motion
<i>MP</i>	Metacarpophalangeal	$R_{i,n,P}, R_{i,n,D}$	Moment arm after joint motion of i th muscle-tendon in n th joint at proximal and distal phalange, respectively
<i>PIP</i>	Proximal interphalangeal	$R'_{i,n,P}, R'_{i,n,D}$	Moment arm before joint motion of i th muscle-tendon in n th joint at proximal and distal phalange, respectively
<i>DIP</i>	Distal interphalangeal	l_1, l_2, l_3	Phalange length of proximal, middle, distal phalanx, respectively
<i>PCSA_j</i>	Physiological cross-sectional area in j th muscle in cost function	F_1, F_2, F_3	Input forces at distal, middle, proximal phalanx, respectively

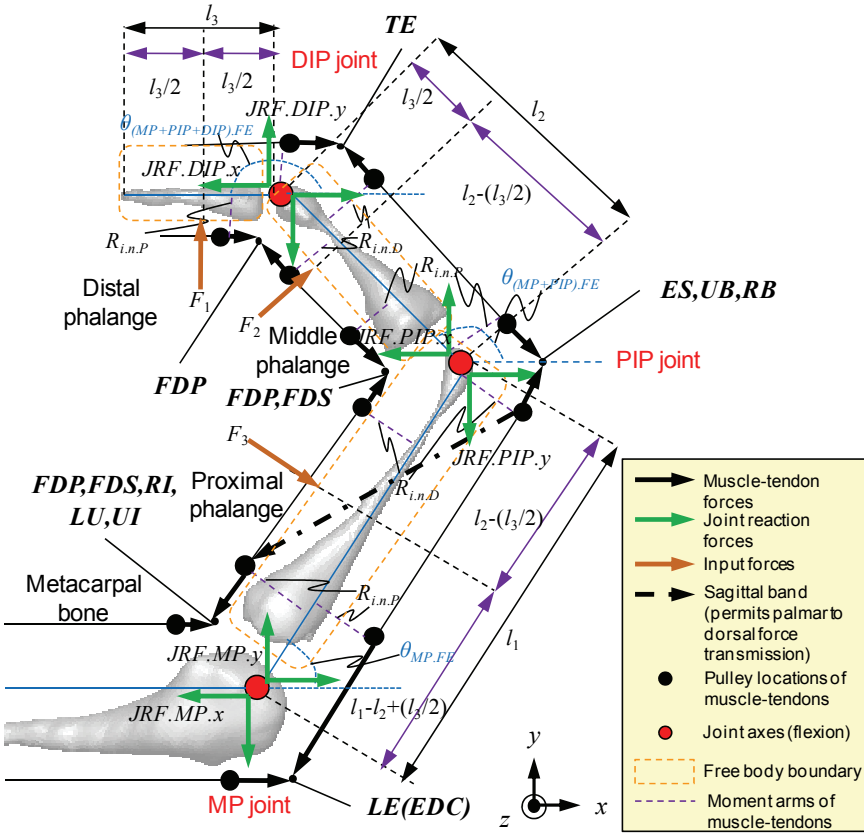


Fig.1 Finger musculoskeletal model in the sagittal plane

II. BIOMECHANICAL MODEL OF FINGERS

Fingers are driven by complicated muscle-tendon networks, and constructing an accurate musculoskeletal model for the whole hand is still an open problem in biomechanics. Therefore, a musculoskeletal model of one finger is proposed in this research. The model is an improved version of the one originally proposed by Fok [3]. We replaced the fixed moment-arm lengths of flexors and extensors in their model with the variable ones in our model.

A. Mechanical Equilibrium Conditions at Finger Joints

Fig.1 shows the biomechanical structure of the proposed muscle-skeletal model for one finger in the sagittal plane. When external forces F_1 , F_2 and F_3 , caused by a grasp exist in the sagittal (x - y) plane and act on midpoints of distal, middle and proximal phalanges, then the following equilibrium of forces and moments (1) (2) must hold at three finger joints (DIP, PIP and MP) for flexion/extension motion in the sagittal (x - y) plane and for adduction/abduction in the transverse (x - z) plane, respectively. This can be written as:

$$\sum_n F_{x,n} = 0, \sum_n F_{y,n} = 0, \sum_n M_{xy,n} = 0, \quad n \in \{MP, PIP, DIP\} \quad (1)$$

$$\sum_n M_{xz,n} = 0, \quad n = MP \quad (2)$$

where, $F_{x,n}$ is a force component in x -direction acting at joint n , and $M_{xy,n}$ is a moment on the sagittal (x - y) plane at joint of

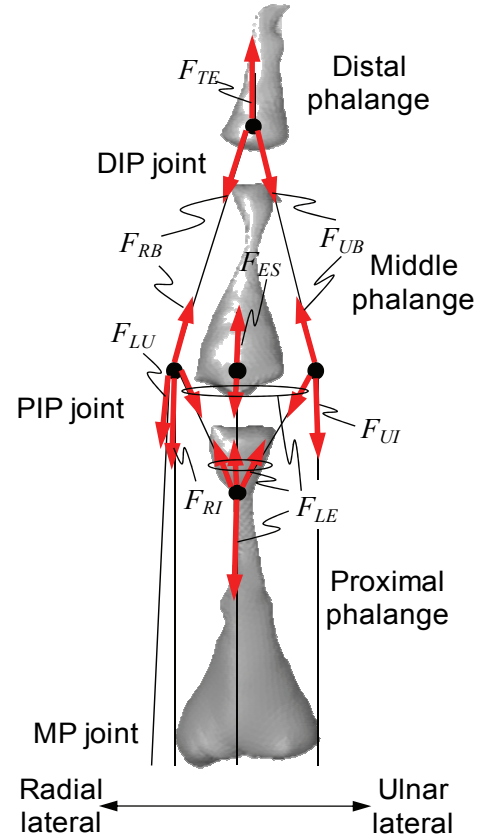


Fig.2 Muscle-tendon network of extensor mechanism in the transverse plane

n . For example, for flexion/extension motion in the sagittal plane at a DIP joint, equation (3) and (4) must hold for forces in the x -direction and for moments in the x - y plane, including the external force, which can be written as:

$$F_{JRF,DIP,x} - (F_{FDP} + F_{TE}) \cos \theta_{(MP+PIP+DIP),FE} = -F_1 \sin \theta_{(MP+PIP+DIP),FE} \quad (3)$$

$$0.7962 l_2 (R_{FDP,DIP,P} F_{FDP} - R_{TE,DIP,P} F_{TE}) = 0.5 F_1 l_3 \quad (4)$$

where, $F_{JRF,DIP,x}$ is a joint reaction force of the DIP joint in the x -direction, F_{FDP} is a muscle-tendon force acting on flexor digitorum profundus, F_{TE} is a muscle-tendon force acting on terminal extensor, and $\theta_{(MP+PIP+DIP),FE} = \theta_{MP} + \theta_{PIP} + \theta_{DIP}$ where θ_{MP} , θ_{PIP} , θ_{DIP} is a flexion/extension angle of MP, PIP and the DIP joint. l_2 and l_3 are the lengths of middle and distal phalanx, respectively. $R_{i,n,P}$, $R_{i,n,D}$ denote the length of moment arm which force acting on a muscle-tendon, i , generates for the proximal (P) or distal (D) bone around a finger joint n , respectively.

As the moment arm lengths actually vary according to the finger joint angles, we introduce a new linear model for them where the arm length, $R_{i,n,q}$, can vary in proportion to finger joint angles as,

$$R_{i,n,q} = \alpha_{i,FE} \theta_{n,FE} + \alpha_{i,AA} \theta_{n,AA} + R'_{i,n,q}, \quad q \in \{D, P\} \quad (5)$$

where $\theta_{n,FE}$ is a flexion/extension angle and $\theta_{n,AA}$ an adduction/abduction angle of a finger joint n , $\alpha_{i,FE}$ and $\alpha_{i,AA}$

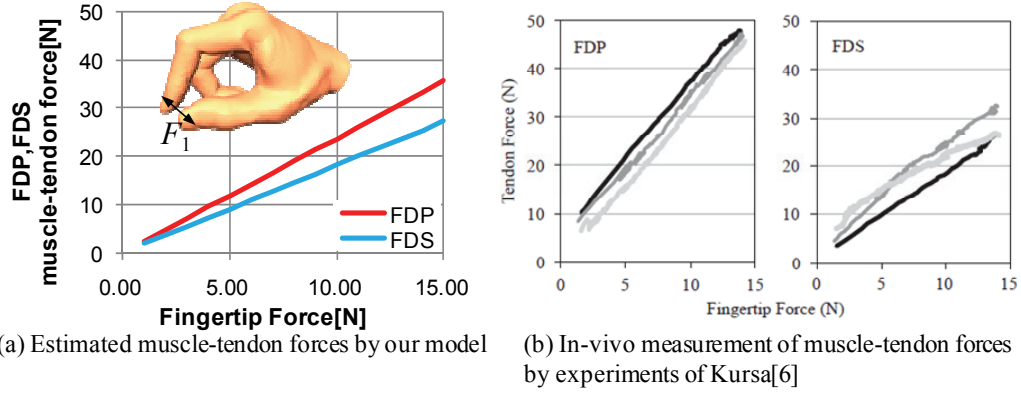


Fig.3 Muscle-tendon forces (F_{FDS} , F_{FDP}) of the index finger in case of pinch posture

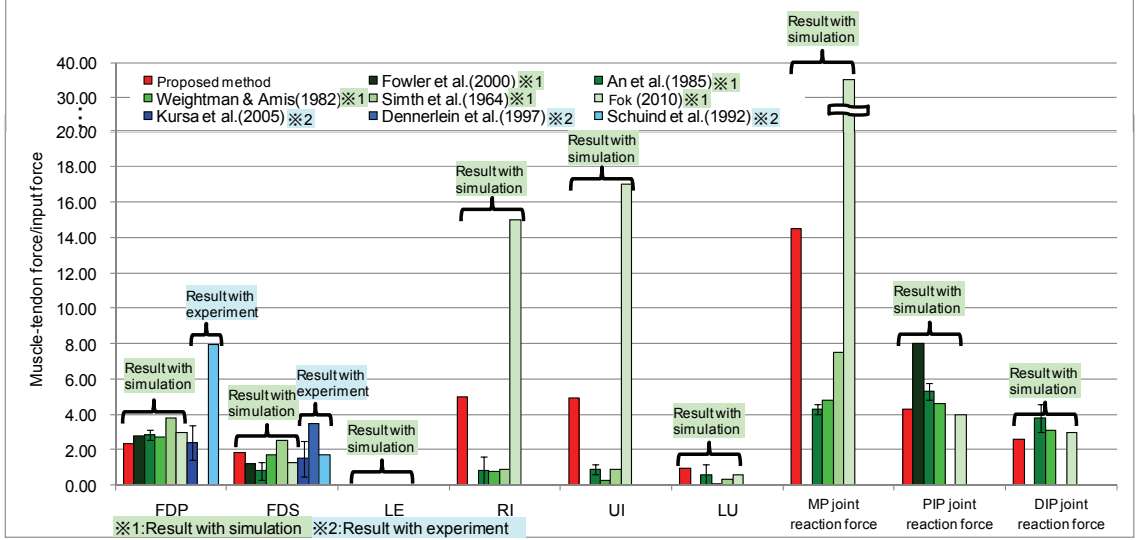


Fig.4 Estimated internal load distribution of the index finger in case of pinch posture

constants of proportion, and $R'_{i,n,q}$ is a fixed value of the moment arm which is normalized by the middle phalanx length. The constant values of $\alpha_{i,FE}$, $\alpha_{i,AA}$ and $R'_{i,n,q}$ were derived from a previous experiment [4].

B. Mechanical Equilibrium Conditions at Finger Muscle-tendon Networks

Fig.2 shows the simplified muscle-tendon network structure of the finger in our proposed model. From the network connectivity of Fig.2, the following equality and inequality conditions (6) on tensile forces acting on finger muscles-tendons must hold at each junction in the band. At the same time, the conditions that all tensile forces must be positive are expressed by inequality conditions (7).

$$\begin{cases} F_{TE} = F_{UB} + F_{RB}, F_{UB} \leq F_{UI} + \frac{1}{2} F_{LE} \\ F_{RB} \leq F_{RI} + F_{LU} + \frac{1}{2} F_{LE}, F_{ES} \leq F_{LE} \end{cases} \quad (6)$$

$$F_i \geq 0 \quad (i \in T = \{UI, RI, LU, LE, FDS, FDP, RB, UB, ES, TE\}) \quad (7)$$

C. Estimation of Finger Muscle-tendon and Joint Reaction Forces based on Non-linear Optimization

When grasping an object, it has been assumed that

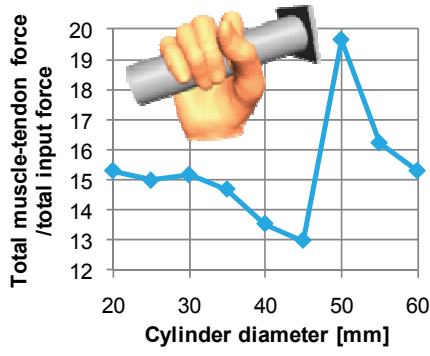
muscle-tendons with larger physiological cross-sectional areas generate more forces and that the total amount of stresses acting on the finger muscle-tendons is minimized [3]. Therefore, in this research, the unknown internal load patterns consisting of finger muscle-tendon forces and joint reaction forces were derived from the solution of the following non-linear optimization problem (8):

$$\text{minimize} \sum_{F_i, i \in T} \left(\frac{F_j}{PCSA_j} \right) \quad (T_m = \{UI, RI, LU, LE, FDS, FDP\}) \quad (8)$$

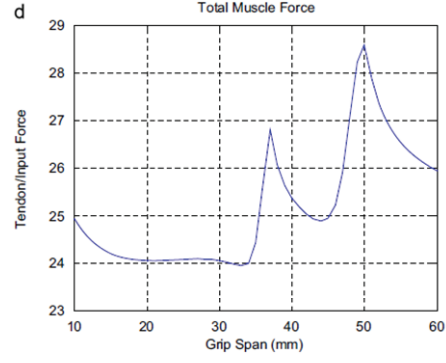
where $PCSA_j$ denotes the physiological cross-sectional areas of a finger muscle-tendon, j , whose values were referred to as the ones in [3,5]. Giving three external force values, F_1 , F_2 and F_3 , as fixed values, we can solve this nonlinear optimization with equality and inequality constraints (1)(2)(6) and (7), then 16 unknown inner muscle-tendon forces F_i ($i \in T$) and joint reaction forces $F_{x,n}$, $F_{y,n}$ ($n \in \{MP, DIP, PIP\}$) can be obtained.

III. MODEL VALIDATIONS AND DISCUSSIONS

The validity of the biomechanical model was examined at two grasp postures; the pinch posture and the power grasp of cylinders with various diameters. In the pinch posture, the



(a) Estimated total muscle-tendon forces by our model



(b) Estimated total muscle-tendon forces by the model of Fok[3]

Fig.5 Total muscle-tendon forces of the index finger in case of power grasp posture

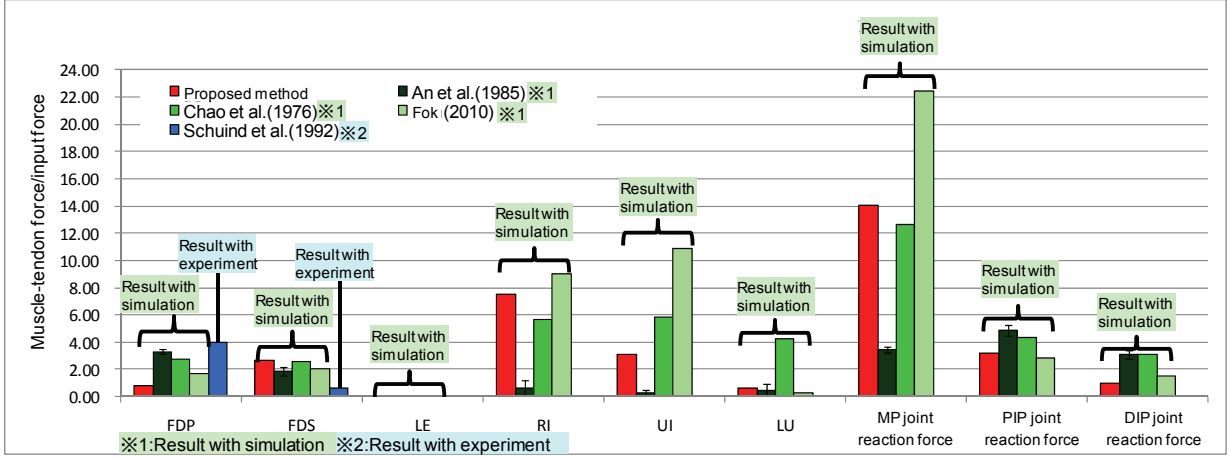


Fig.6 Estimated internal load distribution of the index finger in case of power-grasp posture

finger joint angles of the index finger were set as $\theta_{MP}=45\text{deg}$ and $\theta_{PIP}=35\text{deg}$, and the tip of thumb touches the one of the index. An external force $F_1=1\sim 15\text{N}$ was applied to the finger tips. On the other hand, in the power grasp, plausible grasp postures where a cylinder with diameter of 20mm to 60mm was held were generated using the Digital Hand. External forces, $F_1=15\text{N}$, $F_2=5\text{N}$ and $F_3=10\text{N}$, were applied to each of the phalanxes of all fingers and $F_1=15\text{N}$ to a thumb. Under these conditions, the unknown inner muscle-tendon forces and joint reaction forces were estimated, and they were compared with those of the previous simulations and experiments.

Fig.3 (a) shows the estimated change in muscle-tendon force of the flexor digitorum profundus, F_{FDP} , and of the flexor digitorum superficialis, F_{FDS} , in the case of the pinch. It was shown that F_{FDP} becomes greater than F_{FDS} as the applied force to the finger tip increases, and that this tendency well fits to the previous experiment [6] which is shown in Fig.3 (b). Fig.4 compares the estimated internal load distribution in the pinch posture. Except for F_{RI} , F_{UI} and $F_{JRF.MP}$, our estimated forces agree well with the other simulation results. Our simulation results showed that relatively large forces for F_{RI} , F_{UI} and $F_{JRF.MP}$ are needed to help other muscle-tendons exert enough force. This result can be supported by other simulation results [7]. Therefore, the internal load estimation of the finger

by our model can be considered to be effective in the case of pinch postures.

On the other hand, Fig.5 shows the estimated change in the total muscle-tendon forces in the case of the power grasp. It was shown that the total force decreases as a cylinder diameter increases and takes a minimum at 40mm. This tendency and the amount of the force agree well with the previous experiment [8] and the previous simulation result [3] which is shown in Fig.5 (b). However, in the comparison of muscle-tendon force distribution of Fig.6, F_{FDP} becomes smaller than F_{FDS} , which does not agree well with the previous experiment.

IV. CONCLUSIONS AND FUTURE WORKS

A musculoskeletal model of a finger was proposed to estimate the internal finger load patterns aimed at objective virtual ergonomic assessment of the Digital Hand. The comparison of the estimated results with the previous works showed that the model can be used for the estimation in case of the pinch posture. However, in the power-grasp posture, the total muscle-tendon forces could be well estimated, but the finger internal load distribution could not be predicted well. A possible cause of this disagreement might be that the optimization was executed only by one finger muscle-tendon stresses, and muscle-tendon stresses of all the fingers and the thumb must be optimized simultaneously. This is left as our future work.

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