Biomechanical analysis of the normal and reconstructed human hand: Prediction of muscle forces in pinch and grasp

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Abstract—In this work we present a biomechanical model of the normal and reconstructed human hand. The objective of this model is to predict muscle forces during the following three tasks: tip pinch, key pinch and grasp. The model takes into account all the available tendons in the fingers.

Two common tendon transfers, to reconstruct the pathological hands, are then simulated. The brachioradialis BR transferred to flexor pollicis longus FPL to restore the thumb flexion and the extensor proprius of the index finger EIP transferred to extensor pollicis longus EPL to restore extension and abduction of the thumb. A non linear optimization approach was used to predict the optimal combination of tendons that maximized pinch and grasp strength after repairing hand.

Keywords: Tendon transfer, tendon forces, pinch, grasp

I. Introduction
The coordination among multiple joints and muscles and evaluation of hand strength and tendon tensions during power or precision grasp is of paramount importance in evaluating the state of the hand and determining the effectiveness of various surgical or treatment procedures such as tendon transfers.

Several researchers targeted the development of biomechanical models for the healthy hands. Lbath et al [1], Giurintano et al [2], Cooney et al [3] have developed different models to study muscular and articular forces in the thumb during key pinch. Brook et al. [4] developed a dynamic model of the biomechanics of the index finger during pinch. Vigouroux [5] developed a biomechanical model for the middle finger for crimp and slope grip. Problems of balancing of static forces were solved using different methods electromyography [6], systematic combination of muscular forces or optimization method [7] [8].

Many clinical researches have quantified in experiments deficits in the pinch strength and tendon forces in the pathological and repaired human hands [9], [10]. Others have examined surgical procedures such as tendon transfers that could be used to restore grasp or pinch function, prevent deformity, dislocations, muscle paralysis and tendon damage [11], [12]. However a little number of researches has simulated tendon transfers in the hand subjected to externe efforts, such as the works of An et al. [13], which consists on the development of an analytic model for the force analysis for pinch and grasp function for normal and abnormal hands.

In this work we propose a biomechanical model, which takes into account the flexors, the extension mechanism in all the long fingers and all the available muscles of the thumb. This biomechanical model is then extended to solve the problem of tendon transfers.

This paper is organized as follows: section 2 details the biomechanical model of the hand. Section 3 presents some simulation results in the case of the normal hand and in the case of the reconstructed one. We were interested in restoring the mobility of the thumb, which is the most important finger in all types of grasps. Some concluding remarks are presented in section 4.

II. Biomechanical model of the human hand
A. Anatomical model
The thumb was modeled by three segments. The interphalangeal IP joint was modeled as frictionless hinge with one degree of freedom in flexion/ extension. The metacarpophalangeal MCP and the carpometacarpal CMC joints were modeled with two degrees of freedom in flexion/extension and in abduction/adduction. The complex function of the thumb, including flexion/extension, abduction/adduction, and composite motions of opposition and circumduction is the result of the specific anatomical structures of the CMC joint. The thumb has 8 muscles: The flexor pollicis longus FPL, the extensor pollicis longus EPL, the abductor pollicis brevis APB, the adductor pollicis ADD, the extensor pollicis brevis EPB, the flexor pollicis brevis FB, the abductor pollicis longus APL and the opponens pollicis OPP.

Each long finger: the index, the middle, the ring or the little, was biomechanically modeled by 4 rigid segments: proximal, middle, and distal phalanx and metacarpal bone. Distal interphalangeal DIP and proximal interphalangealPIP joints were modeled as frictionless hinges with one degree of freedom in flexion/extension. The MCP joint was modeled with 2 degrees of freedom in flexion/extension and in abduction/ adduction.
The index finger (I) has 7 muscles: the flexor digitorium profundus FDP(I), the flexor digitorium superficialis FDS(I), the extensor digitorium communis EDC(I), the extensor indicis EI, the lumbrical LUM(I), the radial interosseous RI, and the ulnar interosseous UI. And we take in addition into account the complicated extension apparatus, which consists of a tendinous extensor network that wraps over the dorsum of the finger’s phalanxes: the terminal extensor TE, the extensor slip ES, the radial band RB, and the ulnar band UB. The middle (M) finger has 6 muscles FDP(M), FDS(M), EDC(M), LUM(M), the second dorsal interosseous SDI, and the third interosseous SI. The little(L) has 8 muscles FDP(L), FDS(L), EDC(L), LUM(L), the fourth dorsal interosseous FoDI, the second palmar interosseous SPI, and the third palmar interosseous TPI.

In conclusion, the total number of muscles is 35 and the number of degrees of freedom is 21. We can notice that the human hand is a redundant system since there are more muscles than degrees of freedom. For instance, a number of different muscle coordination strategies can result in the same output force from a finger, and determining which muscles are contributing and to what extent, becomes challenging.

B. Analytic model

Optimization approaches is used to resolve the redundant problem in simulating the human hand by minimizing an objective function under some constraints. We used the summation of the total quadratic muscle stress (1) as the objective function in the optimization procedure to estimate the muscle forces [7].

\[ J = \sum_{i=1}^{n} \left( \frac{F_i}{PCSA_i} \right)^2 \]  

(1)

With \( n \): the total number of tendons, \( PCSA_i \) is the physiological cross-sectional area of the \( i \)th muscle.

For each joint of the fingers we can write the equilibrium equation in moments as:

\[ \sum M_{ij} + \sum M_{Fexij} = 0 \]  

(2)

Where:

- \( M_{ij} \): Moment of tendon \( i \) at joint \( j \) (\( j = CMC, MCP, IP, PIP, DIP \)).
- \( F_i \) the tension in tendon \( i \).
- \( M_{Fexij} \) is the moment of the external forces of the joint \( j \).

To solve in simplifying the indeterminate set of static equilibrium equations a set of constraint equations is derived. These equations represent the interaction among the forces of the extensor mechanism where the tendons interconnect [4].

\[ F_{j} = z_{ij} F_{ij} + z_{jk} F_{kj} \]

\[ F_{ij} = \alpha_{ij} F_{ij} + \alpha_{il} F_{il} + \alpha_{lj} F_{lj} \]

\[ F_{ij} = \alpha_{ij} F_{ij} + \alpha_{il} F_{il} + \alpha_{lj} F_{lj} \]

(3)

With: \( \chi_{ij} = 0.992, \chi_{ij} = 0.995 \) reported from [4].

Thus, the non linear optimization problem for the calculation of muscle forces in the human hand could be formulated as:

- Find: \( \{ F_i \}, i=1:35 \)
- Subject to:

\[ 0 \leq \alpha_{ij} \leq 0.5, \ 0 \leq \alpha_{il} \leq 1, 0 \leq \alpha_{lj} \leq 1 \]

(4)

(5)

The equilibrium constraints as expressed in (2).

B.1 Equilibrium constraints

Adapting Eq. (2) to the five degrees of freedom of the thumb finger model provides a five moment equilibrium equation system:

\[ M_{CFCM} + M_{PFM} + M_{FEM} = 0 \]  

(6)

\[ M_{CFCM} + M_{PFM} + M_{FEM} = 0 \]

(7)

\[ M_{CFCM} + M_{PFM} + M_{FEM} = 0 \]

(8)

\[ M_{CFCM} + M_{PFM} + M_{FEM} = 0 \]

(9)

\[ M_{CFCM} + M_{PFM} + M_{FEM} = 0 \]

(10)

Adapting Eq. (2) to the four degrees of freedom of the index finger model provides a four moment equilibrium equation system:

\[ M_{TE/DIP} + M_{FDP-LUM/DIP} + M_{FEX/DIP} = 0 \]  

(11)
\[ M_Z = M_{Z(\text{FDP-LUM})/\text{PIP}} + M_{Z(\text{FDS/PIP})} + M_{Z(\text{ES/PIP})} \]
\[ + M_{Z(\text{RB/PIP})} + M_{Z(\text{UB/PIP})} + M_{Z(\text{ES/PIP})} = 0 \]  
\[ (12) \]

\[ M_Y = M_{Y(\text{FDP-LUM})/\text{MCP}} + M_{Y(\text{FDS/MCP})} + M_{Y(\text{ES/MCP})} \]
\[ + M_{Y(\text{EDC/MCP})} + M_{Y(\text{EI/MCP})} + M_{Y(\text{ES/PIP})} = 0 \]
\[ M_Y = M_{Y(\text{EDI/MCP})} + M_{Y(\text{LUM/MCP})} + M_{Y(\text{UI/MCP})} \]
\[ + M_{Y(\text{UI/MCP})} + M_{Y_F(\text{MCP})} = 0 \]  
\[ (13) \]

\[ (14) \]

Where:  
- \( M_Z \): The moment of flexion/extension with respect to the \( Z \) axis considered as flexion axis.  
- \( M_Y \): The moment of abduction/adduction with respect to the \( Y \) axis considered as abduction axis.

With the same way, we write the equilibrium equations for the other fingers, and we obtain twenty one equilibrium moment equations and fifty unknowns to predict.

**B.2 Hand configuration**

The joint orientation angles for the different grasps are summarized in Table I.

<table>
<thead>
<tr>
<th>Joint angles</th>
<th>Tip pinch</th>
<th>Key pinch</th>
<th>Wide Grasp</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMC flexion</td>
<td>-24</td>
<td>-40</td>
<td>-10</td>
</tr>
<tr>
<td>CMC abduction</td>
<td>25</td>
<td>10</td>
<td>-20</td>
</tr>
<tr>
<td>MCP flexion</td>
<td>25</td>
<td>15</td>
<td>-30</td>
</tr>
<tr>
<td>MCP abduction</td>
<td>5</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>IP flexion</td>
<td>30</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Index/PIP flexion</td>
<td>60</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>MCP abduction</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PIP flexion</td>
<td>45</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>DIP flexion</td>
<td>25</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table I. Joint angles for different studied grasp functions**

The moment arms data were obtained for long fingers from [15], [6] and from [16] for the thumb.

**B.3 Tasks loadings**

We used the maximal strengths of the studied grasps (Table II) measured by An et al. [13] to obtain realistic values of the forces.

<table>
<thead>
<tr>
<th>Hand function</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip pinch</td>
<td>95</td>
</tr>
</tbody>
</table>

**Table II. Average strength (Newtons) of index finger in isometric hand functions**

In normal tip pinch, the thumb is flexed slightly and the IP joint is extended or only slightly flexed. For a static grasp function, when more than two digits are involved in the grasp used to oppose the thumb force, the total force produced by the fingers must equal that of the thumb. The average contribution of the index to the total grip force is 33%, for the middle one 33%, for the ring 17% and for the little 15% [17]. The maximal index-tip force considered was 109N (Table II) directed perpendicularly from the midpoint of the distal phalanx in the plane of finger flexion-extension. The particularity in a wide grasp function that all the forefinger joints are slightly flexed, the thumb is in an extension/adduction position.

**III. Results and Simulations**

We present in the following section, the results concerning the distribution of tendon forces obtained by the model for the thumb and the index finger.

**A. Prediction of tendon forces for the healthy human hand**

![Fig. 1. Distribution of muscles forces (in unit of applied force) in thumb finger](image1)

![Fig. 2. Distribution of muscles forces (in unit of applied force) in index finger](image2)
A.1 Distribution of tendon forces for pinch function

In pinch function (figure 1), the IP and the MCP joint were in flexion. This induces the fact that FPL and FPB are strongly activated. The extensor EPL is slightly active, the EPB is inactive as found by Cooney and al. [3], because they act in the same direction as the external thumb-tip force. The absence of effort in the opposens pollicis OPP is explicated by the great effort in FPB, whose acts as opposant. The APL was strongly activated because the CMC joint was in abduction extension position. The FDP, EI and the two radial intrinsic muscles RI and LUM have consistently high force values compared with other muscles (figure 2). The FDS, EDC carried minimal load in key pinch. The balance of the MP joint to prevent ulnar deviation was mainly due to the action of the RI in key pinch and the RI, and UI in tip pinch. This created a large flexion moment at the joint that required counteraction of the long extensor for balance, that why the EI was strongly active. The intrinsic muscles appeared to produce more force during pinch than grasp function to stabilize the MP joint. (The ratio of the radial interosseus in the case of grasp function was equal to 1.25, whereas it was equal to 7 in the case of key pinch function.

We increased the tip-force applied, and we kept the same configuration for the thumb and the index finger. The tendon tensions predicted (figure3-4) are proportional to the key pinch force. Therefore, one can state that the model relating the forces in the different tendons with the external loading is linear.

This linearity was validated also for the others grip function, and the external grip force in the tip of each finger $F_{tip}$ can be written as:

\[
F_{tip} = \sum_{i=1}^{n} \alpha_i F_{m_i}
\]

Where: $n$: the number of tendons in a finger.

A.2 Distribution of tendon forces for the wide grasp function

In the case of grasp function, the long fingers’ extrinsic muscles FDP, FDS, EDC provide the major gripping force (figure 1). The FDP and FDS the control respectively the DIP joint’s flexion and the PIP joint’s flexion. The EDC balances the equilibrium of all joints through the extensor mechanism. The major intrinsic muscles involved to control MCP flexion are the RI and the LUM, whereas the EIP of the index was inactive.

For the thumb, the FPL was inactive, only the extensors EPL, EPB, APL and EPL were activated providing MCP extension, incase of the wide grasp, the ADD, APL, OPP stabilize the MCP and the CMC joint. Giurintano et al. [2] report that the FPL is inactive also for a wide grasp. Whereas Towles et al. [18] demonstrate that the magnitude of FPL’s endpoint force increased significantly from 0.5 to 1.6 as the thumb’s position went from the narrow to the wide grasp.

B. Prediction of muscle forces for the reconstructed human hand

B.1 Model of the reconstructed human hand:

We remove the injured tendon and we replaced it by the donor tendon. We suggest tendon forces superimpose linearly, thus $F_{tip}$ is written as:

\[
F_{tip} = \alpha_0 F_{m_0} + \sum_{i=1}^{n-1} \alpha_i F_{m_i} + \alpha_0 F_{i_0}
\]

Where: $\alpha_0$ is the index of the transferred tendon.

$F_{tip}$ can be written as:

\[
a^t \mathbf{F} = F_{tip}
\]

Where:

$a^t = \{\alpha_i\}_{i=1}^{n-1}$ and $\mathbf{F} = \{F_{m_i}\}_n$

To find the optimal combination of tendon forces $\mathbf{F} = \{F_{m_i}\}_n$ in the reconstructed hand, we can
formulate our problem as follows:
Find the maximum of \( F_{t_{ip}} = a^T F \)

Subject to:
\[
\sum_{i=1}^{n-1} r_{q,i} \times F_{m_i} + r_{q,j} \times F_{q_j} + M_{kl} = 0 \tag{18}
\]
\[
0 < F_{m_i} < F_{\text{max}} \tag{19}
\]

\( k \): the type of motion, i.e., flexion/extension or abduction/adduction.
\( l \): the joint CMC, MCP, IP.
\( M_{kl} \): Joint flexion moment generated by the external tip force

**B.2 Surgical restoration of the thumb flexion**

With the FPL completely inactive, no pinch force can be generated, since the IP joint was no longer able to maintain its normal joint configuration. The model predicted that the flexion moment of the IP thumb joint would be lost and that the joint would be hyperextend as the result of the pull of the EPL extensor.

Multiple potential donors for transfer to restore thumb flexion are available. These donors include the extensor carpi radialis brevis ECRB, the extensor carpi radialis longs ECRL [19], the flexor carpi ulnaris FCU, the flexor digitorium superficialis FDS of the ring finger [20]. Omer et al. [21] report the reanimation of the thumb flexion by the transfer of the brachioradialis BR (figure 7) on the paralyzed flexor FPL, to improve the key pinch. The choice of BR as a donor muscle is based on its strength (physiological cross sectional area).

**B.3 Surgical restoration of the thumb extension**

The EPL was the only extensor of IP joint of the thumb. Then, incase of EPL rupture, IP can be passively but not actively extended and the thumb pinch is weakened. Potential donors to restore the thumb extension function include the FDS of the middle finger, the FDS to the little finger, the PT (pronator teres) [23] etc... The EIP is the preferred donor (figure 9), because of its strength [24].

With the brachioradialis BR transferred to FPL, the model gives maximum grip force which is obtained by maximizing the magnitude of the grip force and the involved distribution of tendon forces (figure 8).
finger after EIP-EPL transfer- Case of tip pinch

Using the same optimization procedure as in the last tendon transfer, average key pinch strength recovery, as percentage of the uninjured hand, was 92%, and average tip pinch strength was computed to 80%.

V. Conclusion

A biomechanical model of the human hand was presented in this work. This model allowed us to predict the muscle forces in the normal human hand as well as in the case of the reconstructed one. Tendon transfers were used to repair the pathological hand. We treated the problem of restoring the mobility of the thumb, which is the most important finger in all types of grasps. Although precise pathologies cannot be duplicated with analytic models, a correlation between lesions and internal tendon force variations can establish a valid pattern to study their biomechanical effects. For the future work, we will integrate musculo-tendon model in the human biomechanical one to deeply study each transfer.

References