# Force Model for Control of Tendon Driven Hands

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## Abstract

Knowing the tendon forces generated for a given task such as grasping via a model, an artificial hand can be controlled. A two-dimensional force model for the index finger was developed. This system is assumed to be in static equilibrium, therefore, the equations of equilibrium were applied at each joint. Constraint equations describing the tendon branch connectivity were used. Gaussian elimination was used to solve for the unknowns of the Linear system. Results from initial work on estimating tendon forces in post-operative hands during active motion therapy were discussed. The results are important for understanding the effects of hand position on tendon tension, elastic effects on tendon tension, and overall functional anatomy of the hand.

Keywords: Artificial Hand, Tendon Driven Manipulators, Hand Biomechanics, Multi-fingered Robotic Hands, Functional Anatomy, Hand Therapy, Clinical Applications, Force Model, Robotics, Prosthetics.

# 1 Introduction

From studying the functional anatomy of the hand, robotic and prosthetic manipulators have developed to complex designs such as tendon driven manipulators. Although tendon driven hands are complex and difficult to implement, they have many advantages. A tendon driven manipulator allows for a much lighter and streamlined design by placing the actuators in regions more proximal to the hand (e.g. forearm or shoulder area) as opposed to installing them along the joint axes. As a result, more power can be focused on moving the load rather than driving the weight of the motors themselves. The load of the manipulator becomes of greater importance in prosthetics, where the client may be a 50 year old amputee rather than a robotic arm on the assembly line in a manufacturing plant. Those tendon driven systems that make use of elastic elements also offer the advantage of reducing failures such as wear and tear on linkages and joints due to frequent impact of end effecter.

To further designs of artificial hands, a better understanding the of the biomechancis of the human hand must be considered. Therefore, a kinetic model of the human hand is necessary to understand the forces within the hand as well as for control of future artificial hands. If a model existed that predicted the tendon forces that are present when a hand is subjected to external loads, then this hand can now be controlled. By using the model to predict the forces in the tendon for various tasks such as grasping, manipulating, and pushing, the known tendon forces can be used as the input to a neural network and trained to recognize a specific task. After the network is trained, the manipulator can then be controlled for similar tasks as ones used to train the system. For a model to be accurate in predicting the tendon forces in the hand, it is necessary to have the proper biomechanics included. For example, the model must include the proper axes of finger/hand if acceptable grasp is to be obtained. Also, the proper moment arms and considering the elastic property of muscle/tendon unit is very important to insure accurate results of tendon force.

## 2 Background

The goal of artificial hands in the fields of robotics and prosthetics has always been the same. Each field is still on the quest for the most anthropomorphic hand. Because of stiff design restrictions imposed upon prosthetic hands (e.g. size, weight, functionality, and appearance), the advancement in technology towards a truly anthropomorphic hand has been very slow. In comparison, robotic hands not having those severe design restrictions have risen to a much higher level of dexterity as their hand designs have become more anthropomorphic. These designs contain multi-fingered hands and actuation and power transmission through tendons much like the human hand.

Two tendon driven hands considered the pioneers in the field of robotic hands are the Stanford/JPL Hand (Salisbury Hand) [1] and the Utah/MIT Hand [2]. Although both of these designs showed many anthropomorphic characteristics, they lack anatomically correct joints and tendon configurations; as a result the kinematics and the dexterity of the hand are limited. Recent work on an anatomically correct finger model, the ASU finger [13], emphasizes the importance of human anatomy. This model was used for experiments in motion/control, excursion, and pathomechanics of the finger.

Future work in tendon driven anthropomorphic hands will take advantage of new developments in artificial muscles and advances in kinematics of human hands and arms [7, 8, 9]. A tendon-driven system can naturally make use of advances in artificial muscles such as the ionic polymer gel muscle [10, 11, 12]. With these promising new artificial muscles, the objective of making an artificial hand as anthropomorphic as possible is not far away,

Initial work on a model for estimating tendon forces during active motion therapy has been done [4, 3]. A simplified model was used to predict tendon forces that were generated during post-operative active motion hand therapy. In therapy the patients were required to actively resist a load placed on their finger. The wrist and joints of the fingers axe restricted to movements in the flexion/extension axis of rotation. It is this model that will be presented and discussed in this paper.

## 3 Development of Model

### 3.1 Definition of Model Elements

Our model is based on the musculoskeletal anatomy of the human finger, the index finger. This finger contains four bone segments (metacarpal, proximal phalanx, middle phalanx, distal phalanx) and four joints (carpometacarpal (CMC), metacarpophalangeal (MP), proximal interphalangeal (PIP), and the distal interphalangeal (DIP)). There are seven muscle/tendon that control its motion and function, extensor digitorum communus (ED C), extensor indicis (EI), flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), ulnar interosseous (UI), radial interosseous (RI), and lumbrical (LUM) muscles. Tendons are attached to the end of muscles and run along the surface of bone spanning multiple digits finally inserting into the periosteum (fibrous outer layer of bone). As the tendon is followed distally from the muscle it is found to have a complex arrangement where a tendon may bifurcate into tendon branches or even coalesce into a fibrous sheath as is found in the aponeurosis. Figure 1 shows the skeletal system for the index finger and an example of muscle and tendon complex, the FDP.

### 3.2 Mechanical Analysis

Different mechanical analogs are used in our model in accordance to the physiologic functions and anatomic constraints of finger joints. The tendon assembly (tendon and tendon sheaths) are modeled as frictionless cable-and-pulley system, and the bone segments in the hand are modeled as rigid links. Each joint is modeled as hinge pins, and since only rotations about the z-axis are considered, modeling only one degree of freedom for the two more proximal joints (CMC and MP) is valid.
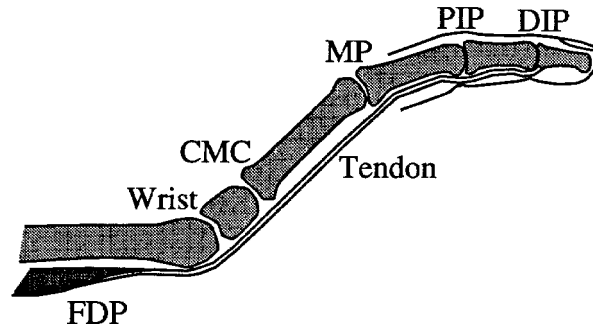
Figure 1: Musculoskeletal Anatomy of Index Finger

There are four joints in our finger model (hindge pins) and therfore, for degrees of freedom. The joints of the finger also called articulations are the functional junction between the digits. The finger is viewed as a kinematic chain and when it is subjected to a load, it is also a closed kinematic chain.

There is a total of five coordinate systems used to define the model, one fixed coordinate system and four moving coordinate systems. The fixed coordinate system is located at an arbitrary position away from the finger. The moving coordinate systems are located at the center of the joint axes for all joints (CMC, NIP, PIP, DIP). A moving coordinate system at each joint is used to easier define the location and orientation oft endon and applied force(s). It also facilitates the ease of defining reaction forces, moments, and relative rot ation between digits. The underlying assumptions and conditions for our model include the following:

1. Normative hand model

2. Force along tendon is constant

3. Moment arms are constant

4. No subluxation of joints during isometric exercise (Stability of joints maintained)

5. Insertion bands of intrinsic muscles/tendon have a single line of action

6. Radial and ulnar lateral bands as well a radial and ulnar interossei are combined using their average moment arm

## 3.3   Mathematical Model

The entire system is said to be in static equilibrium, implying that each joint must also be in static equilibrium. Therefore, the equations of equilibrium at each joint can be expressed as

$$\sum_{i=1}^{n} \left[\vec{F}_{tendon}\right]_i + \sum_{j=1}^{m} \left[\vec{F}_{external}\right]_j + \vec{F}_{reaction} = 0 \tag{1}$$

$$\sum_{i=1}^{n} [M_{tendon}]_i + \sum_{j=1}^{m} [M_{external}]_j = 0 \tag{2}$$

where

$\left[\vec{F}_{tendon}\right]_i$ = tendon force vector

$\left[\vec{F}_{external}\right]_j$ = applied force(s)

$\vec{F}_{reaction}$ = joint reaction force

$[M_{tendon}]_i$ = tendon torque $-\left[\vec{F}_{tendon}\right]_i \cdot [r_{tendon}]_i$

$[M_{external}]_j$ = applied torque $\left[\vec{F}_{external}\right]_i [r_{external}]_i$

$[r_{tendon}]_i$ = tendon moment arm

$[r_{external}]_i$ = position vector of $\left[F_{external}\right]_j$ wrt coordinate center

The elastic component of resistance due to soft tissue varies with the joint angle. Llorens [15] approximated this with a three piece elastic model as in Equation 3 and illustrated in Figure 2.

$$k = \begin{cases} 50g - \text{cm/degree} & \cdots \alpha < \alpha_e \\ 15g - \text{cm/degree} & \cdots \alpha_e \leq \alpha \leq alpha_f \\ 50g - cm/degree & \cdots \alpha > \alpha_f \end{cases} \tag{3}$$
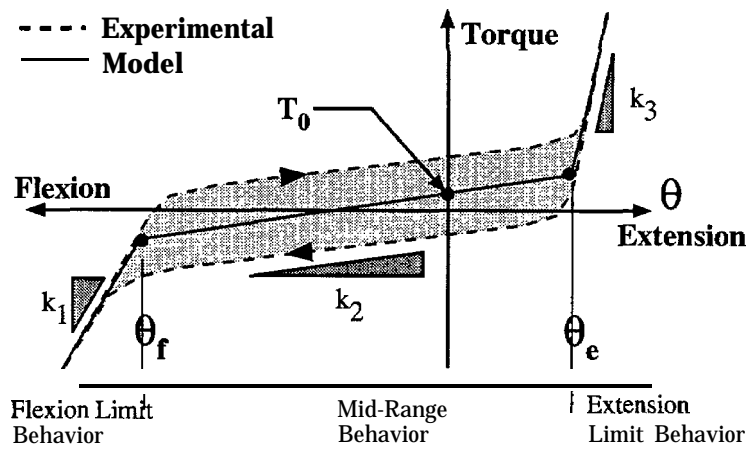


Figure 2: Passive Elastic Torque vs. Angle Curve

The constraint equations are equations that describe how tendon system is interconnected. As an example, in the aponeurosis we find a network of tendons connected together at several points (nodes). Therefore these equations will appear in the form:

*Vectoral* sum *of tendon forces =Vectoral sum of other tendon forces*

or as a specific example at the MP-joint:

$$F_{extensor} + F_{interossei} + F_{Lumbrical} = F_{Lateral\ Bands} + F_{Central\ Slip} \tag{4}$$

We end up with n-equations and n-unknowns. The entire system is linear, and can be expressed as

$$[A]x = b \tag{5}$$

where [A] is the coefficient matrix, $x$ is the solution vector of unknown forces, and $b$ is the vector for values of RHS of equation 4. Since the system is linear, we can use the technique of Guassian Elimination, which transforms the coefficient matrix [A] to a lower times the upper triangular matrix, the process called LU decomposition. Once in this form, the unknowns are easily solved using back substitution.

# 4 Results

There were two cases considered to examine our model: tendon forces with varying joint angle, and tendon forces with the elastic component of soft tissue added. The first case was to demonstrate the effect of finger position on tendon tension. With the wrist extended, the fingers were placed in a nuetral position (no force in tendons) then the fingers were moved into extension only allowing rotation about the MP joint. Calculations were performed with incrementing values of MP joint angle (35-80degrees) to determine the force generated in the EDC. It was found that as the angle increased into extension, the force in the EDC increased significantly from O-g to 1200-g. If the wrist was slightly flexed, the forces in the EDC would decrease because wrist motion influences a change in the length of the flexor tendons resulting in a change of resting angles for the joints.

The second case was considered to demonstrate the elastic effects at the end of motion. An external load of 50g was applied to the middle of the terminal phalanx while the hand was maintained in a tightly flexed fist. This situation allows considerable elastic restoring moments to be generated by large flexion angles. Calculations were performed to determine the flexor tendons (FDS,FDP) forces. The results showed that even for a very small applied load, large forces were generated in the flexor tendons (2050-g FDP and 1650-g FDS). It is important to note that these forces exceed the gapping strength at repair site of the tendon ( 1600-g).

From the results of these two cases, recommendations for finger loading to insure least potential of rupturing repaired tendons can be made. For example, it is wise not to approach the end limits of range of motion for joints to avoid high levels of generated tendon forces.

# 5 Conclusions

A two-dimensional force model fort he index finger was developed, and results from initial work on estimating tendon forces in post-operative hands during active motion therapy were discussed. The results showed that there is a significant effect on tendon force for varying joint positions and elastic resistance. It was shown that the magnitude of tendon force in the EDC tendon reached as high as 1200-g under no load for finger extension about MP joint, and the magnitude of force for the FDP tendon reached as high as 1650-g for finger in flexed fist position. With these findings guidelines for active motion therapy were established.

The results are important for understanding the effects of hand position on tendon tension, elastic effects on tendon tension, and overall functional anatomy of the hand. Although it is important to note that this model is very naive because it lacks complexity in certain aspects. One aspect is the assumption of constant moment arms may not be a valid assumption especially for the larger joints (wrist). Another aspect is including a model for the muscle/tendon actuator. Currently, this model defines the tendon force as the total force in the tendon instead of total force being defined as the sum of the tendon and muscle forces. Including the model for the muslce/tendon actuator would account for these components, but it would add another level of complexity to the model. The addition of these aspects to the model will be explored in future work.

An extension for the application of this model is the use of the model to predict required force input of an anthropomorphic exoskeletal structure to reduce fatigue of astronauts during tasks that require hand function. This continues to be an ongoing problem for NASA, and recently there has been an effort made in exploring the use of artificial muscles embedded into the space suit to aid the mobolity of astronauts hands [11, 12].

# Acknowledgements

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