# CAD-Based Biomedical Modeling and Visualization

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## 1 Introduction

Computer Aided Design (CAD) plays an important role in the design and development of man-made products and provides significant information concerning design parameters and functional assessment. CAD tools can also be successfully applied to the visualization, modeling and analysis of natural systems: in this case, parts of the human body, specifically the spine and the finger. This work represents a newly developed foundation of a framework with which such natural systems can be graphically visualized and modeled.

Predecessors to this system have been developed to model kinematic aspects of natural systems. For example, Buford and Thompson [4] describe a system for 3D interactive simulation of hand biomechanics. Delp et al. [10] and Hoy et al. [21] describe a graphics based system used to model the lower extremities. This approach provides a framework permitting a more complete functional modeling of natural systems.

Although we have explored both a spinal visualization and analysis system and a finger modeling system, we describe here the computer model of a mechanical finger (henceforth referred to as MFMS: MECHANICAL FINGER MODELING SYSTEM) which was built to simulate a generic human finger. The MFMS permits the study of relations between bone, muscle and tendon, in addition to geometric and static properties of the finger. A specific application addressed is the determination of the existence of one to many mappings between tendon lengths and finger joint angles. For a given set of tendon lengths determined by the application of muscle forces from the extrinsic muscles of the finger, there exists more than one set of joint angles that the finger can assume. This research shows, in the case of an anthropomorphically motivated mechanical finger model, that there can be more than one finger position with the exact same tendon lengths. This can be carried over to the human finger model and is a key concept for the understanding of joint position perception by the finger. Figure 1 shows the user interface and display windows of the MFMS.

The MFMS includes the construction of a mathematical model of the finger, a graphical model of the finger, a dynamic user interface with which to interact with the model, and the interpretation of the resulting data - specifically, the visualization of the six-dimensional data inherent to the one to many mappings.

The general framework used to develop MFMS is shown in Figure 2. The MFMS research benefits both the fields of robotics and bioengineering. By using the MFMS, preliminary designs of robot hands can be accelerated, allowing for an early assessment of the success of a particular design strategy. A system with the visualization capabilities discussed herein becomes a very useful tool for a physician to use in that real-time animations show a patient just what the result of a certain operation will be.

Orthopedics can benefit in the area of constructive surgery from future generations of MFMS type systems. With them a surgeon can determine favorable positions for tendon attachment and bone fusion. The MFMS provides the first steps and a basic foundation for more detailed studies which will aid in the development of systems specific to the aforementioned problems.

## 2 Finger Modeling

The hand is complex and functionally unique. Understanding the biomechanics of the hand and developing a model by which one can correctly simulate hand motion and predict such motion given applied forces and constraints would be extremely beneficial. (See Thompson and Giurintano for an example of a functional hand model [25].) Physicians, especially orthopedic surgeons, would be able to rely on the model when reattaching tendons or repairing a maimed hand. Unfortunately, such a model is extremely difficult to build due to the absolute precision required. The hand, due to its complexity, is still not well understood and is still a topic of research. (See Chao et al. [5] or Nordin [23] for a detailed look at hand biomechanics.)

This portion of research centers on the modeling of a mechanical representation of a human finger with the MFMS and determining some of the aspects of how finger movement is coordinated and controlled with respect to tendon length versus finger joint flexion. The simulation will be much like a simulation of the thumb implemented by Buford and Thompson [4] with the added emphasis on tendon length/finger position relationships. Due to the complexity of modeling an actual finger, the mechanical prototype finger (provided by Prof. Clark of the Nebraska Medical Center) is modeled. This finger has metal phalanges (cylinders), joints (cylinders), wire sheaths (glued on), and polymer tendons. These components are connected so as to capture the basic anatomical features and functions of the finger. With this model, different methods of modeling the finger's parts and the complex interactions between these parts can be tested. This lays a foundation for research into the modeling and simulation of an actual human finger.

## 3 Modeling the Mechanical Finger

Figure 3 shows a set of line drawings from the MFMS simulation of the mechanical finger. MFMS only models the phalanges, joints and tendon placements. Tendon sheaths, structures through which the tendon passes as it follows along a phalange, and tendon attachments to bone are approximated as point connections. This simulation runs on the SGI and allows the user to vary the joint angles while the system maintains the kinematics and tendon paths.

Metacarpophalangeal joints of the fingers undergo joint motions in three axes:

1. flexion-extension,
2. abduction-adduction,
3. rotation.

(See Brand [3].) The mechanical model, and thus the MFMS model, takes into account only the tendons affected by the long (extrinsic) extensor and flexor muscles and accompanying tendons (see Giloi [12],

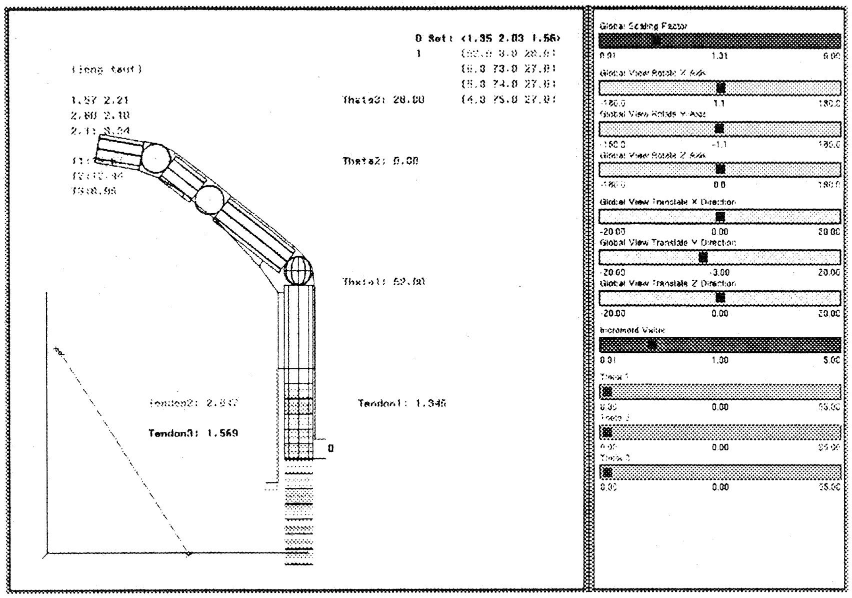


Figure 1: The Mechanical Finger Modeling System (MFMS)

Harris [17, 18], and Ketchum [22]). On the dorsal side is the extensor digitorum muscle and on the ventral side are the flexor digitorum longus and flexor digitorum brevis muscles (Grey [14] and Beck [2]). It is assumed that intrinsic muscles such as the lumbrical muscles, adductor muscles and abductor muscles are not taken into account since their contributions to flexion and extension of the finger are small when compared with that of the long muscles.

MFMS models the mechanical finger in various static positions. Since only the static case is being considered (Clark [6]), viscosity, friction and other such considerations as they are described in Brandt [3] are not included.

Next are added components of interest such as accounting for tendon lengths and predicting finger positioning due to tendon lengths (which are the result of muscle forces). (See Gowitzke [13].) With the completed model it is possible to test its predictive power by measuring parameters and attributes of interest on the actual mechanical finger.

It is very important to have exact measurements of joint size, phalange length, tendon attachment positions, and sheath positions. Very careful measurements of the mechanical finger were taken by hand and then entered into the computer model. The measurements used are presented elsewhere [1].

The computer graphical model (created by using algorithms from Hill [19] and Pokorny [24]) itself consists of four cylinders, each representing a phalange or metacarpal bone. The joints connecting these together are modeled as three cylinders, each of which runs parallel to the axis of rotation through the respective joint. Tendons are represented as lines, and attachments and sheaths are represented as lines drawn out from the phalange to the tendon where the attachment point is. These can be seen in Figure 3.

It should be noted that the dorsal tendon splits as it passes by the proximal phalange. The shorter division connects to the proximal region of the medial phalange while the longer division splits again into two in order to allow the shorter tendon to pass through it, reconnects, and attaches to the proximal portion of the distal phalange. During flexion this idiosyncrasy allows the longer tendon to slide laterally past the joint. This is not taken into account in the mechanical finger nor is it modeled in the computer simulation.

When considering the changes in tendon lengths (caused by contracting muscles) only the length of the tendon changes in the model. For example, if a flexor muscle contracts, the tendon shortens and the finger will flex. Even though this is not the case in real life, it is the case in the MFMS finger model. At the local level of the model, the tendons are said to get longer or shorter as the finger flexes and extends. As the finger flexes, the dorsal tendons get longer and the ventral tendons get shorter. Conversely, as the finger extends, the dorsal tendons get shorter and the ventral tendons get longer.

# 4 Joint Position Perception

Humans are aware of the position of their joints under a variety of conditions (see Horch [20] and Guyton [16]). Whether the joint is static or in motion, whether the eyes are open or closed, humans are still able to perceive the position of most joints. Such position sensing and movement arise from proprioceptive (also called stretch) receptors located within the muscles, skin and soft tissue surrounding the joint. (See Clark [9].) This proprioception is both conscious and unconscious and is paramount for the coordinated movement of our limbs. (See Guyton [15].) This study deals specifically with conscious proprioception.

Naturally, understanding how proprioception is achieved by the human body is an important research area. All joints experience it. The joints in the finger, however, are an exception to the general rule of proprioception. In a study by Dr. F. J. Clark, evidence is presented that there indeed is movement sense (kinetic proprioception) in the index finger, but no position sense (static proprioception). (See Clark [7] and Gandevia [11].) It was shown that movement sense was largely provided by receptors in the skin since a subject with the skin numbed lost the ability to perceive kinetic proprioception. In another study it was shown that position proprioception for the long limbs was partly provided by intramuscular receptors. (See Clark [8].)

## 4.1 Problem Definition

This question of finger proprioception then may be stated: if the limbs have both movement and static position perception, and if finger joints have only movement position perception, and if components of skin receptors provide some static and movement sensory information, and if intramusclular receptors provide some components of static and movement sensory information, then why does the finger not experience static position perception? What is it about the finger's

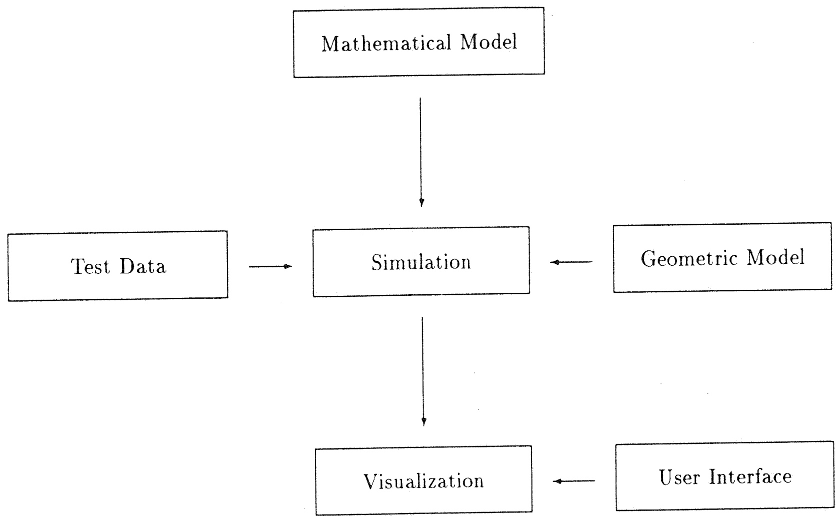


Figure 2: Framework for MFMS

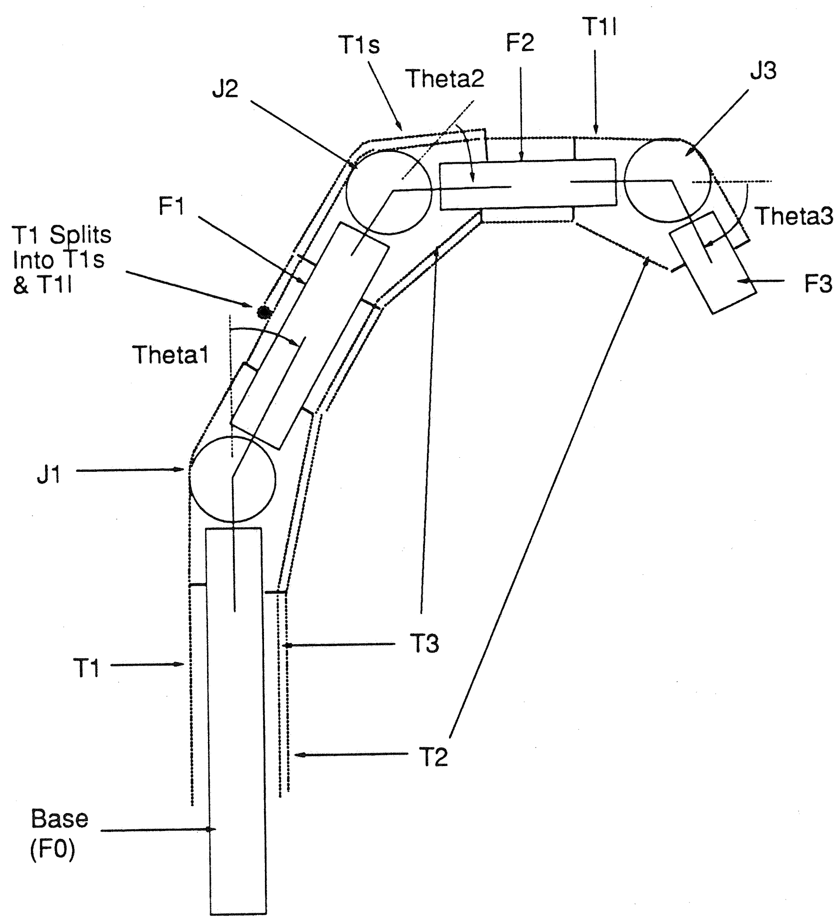


Figure 3: Modeling the Mechanical Finger

anatomical construction and muscular configuration that makes it different from that of the limbs? There is an obvious complexity in the finger with its three joints that play off of each other when in motion to achieve the desired finger position.

The mechanical finger model shows that there is more than one possible set of joint angles for a single set of tendon lengths. That is to say that there is a one to many mapping of tendon lengths to finger positions. This revealing fact adds fuel to the argument that the reason static finger joint position cannot be sensed is that, unlike limbs, fingers are configured in such a way that they can (theoretically) achieve more than one position given a set of lengths, so it is not only the forces applied to the finger that determines the final static position of the finger, but other factors as well. The brain then cannot determine a position of the finger from a given set of muscle forces due to the one to many nature of mapping finger position from muscle forces. (See Clark [7] and Gandevia [11].)

### 4.2 Results From Finger Data

A list of tendon lengths for which multiple joint angles exist was compiled and processed. Several test cases were tried out by hand on the actual mechanical finger to test the one to many mappings. Everything matched the computer's predictions. The model seemed to be correct as far as could be measured.

At this stage there were 6689 such tendon length sets (each such set is called a hit). They were run through a filter which eliminated data sets that were similar. That is to say, if both the tendon length values *and* $\theta$ values of the data sets matched within a certain degree of tolerance, only one was kept and the other discarded. This is unlike earlier when a record was weeded out only if the same tendon triplet matched two hits. There was no consideration of the $\theta$ set. This eliminated data sets which paralleled each other in close proximity, and thus ensured uniqueness of each piece of data. This resulted in 1540 data sets. They are of the form:

$$\{ ( d_1, d_2, d_3 ), ( \theta_1, \theta_2, \theta_3 ) \}$$

where $d_1$, $d_2$, and $d_3$ are the tendon lengths and $\theta_1$, $\theta_2$, and $\theta_3$ are the three $\theta$ values.

Next the data sets were arranged so that all $\theta$s which had matching tendon lengths were grouped together. A data structure was constructed in which a unique triplet of tendon lengths had associated with it a linked list of corresponding $\theta$ triplets as follows:

$$\left\{ ( d_1, d_2, d_3 ), ( \theta_1, \theta_2, \theta_3 )^+ \right\}$$

This data structure is called a *Dset*. There are 145 *Dsets* present in the data which was produced using $\theta$ increments of one degree to get the tendon length values. There are an average of 17 $\theta$ triplets per tendon length triplet.

Note that without running the data sets through the filter to eliminate similar data sets, there would have been 431 *Dsets*, many of which would have paralleled their neighbors very closely, and which would have caused some difficulties during visualization.

Figures 4 through 6 show the MFMS model of the mechanical finger in three very different positions, all with the same tendon lengths. On the bottom left of the MFMS display window is drawn a graph of the one to many tendon length to finger joint angle mapping.

When a single set of tendon lengths is associated with more than one possible finger position, the only possible explanation is that as one joint rotates and changes the tendon lengths, then the other joints rotate so that for each tendon the combined change in tendon segment lengths equals zero. (See [1] for an explanation of the many to one mapping of joint angles to tendon lengths.)

An interesting observation from the *Dset* data is that the third (most distal) joint's $\theta$ value is constant within each *Dset*. That is to say, for every group of joint rotations which map to one set of tendon lengths, the third joint's angle is the same. Moreover, there are certain values which the $\theta$ of the third joint gravitates towards. An angle between 26 degrees and 30 degrees comes up more than half of the time.

In the finger data there is only one exception to the generalization that the distal joint angle is held constant, and that is for the *Dset* for the tendon length set $< 2.530, 3.050, 1.980 >$. The value of rotation for the most distal joint, (the third angle), of the mapped sets of angles is consistently between 56 and 58 degrees except for a single $\theta$ set where the third $\theta$ is five degrees. The reason for this single exception is unknown.

A plausible explanation for this deals with the ability for the distal joints to compensate for tendon length changes caused by the rotation of the third joint. When the third joint rotates, only two of the three tendons change length. The short ventral does not change length at all. This being the case, not only do the other two joints need to compensate for the distance the two tendons changed, but in their rotations they must also not effect the length of the short tendon which did not change when the third joint rotated. This is highly unlikely and only occurs in the above mentioned case.

## 5 Implications for Robot Hand Control

This analysis of the human hand indicates that, at least for static grasps, the joint angles of the fingers may not be available to the control algorithms. Since almost all current robot grasping strategies rely on joint angle information, this seems to indicate that perhaps another approach to static grasp analysis is required if manipulation skills similar to human ability are desired.


### Acknowledgements

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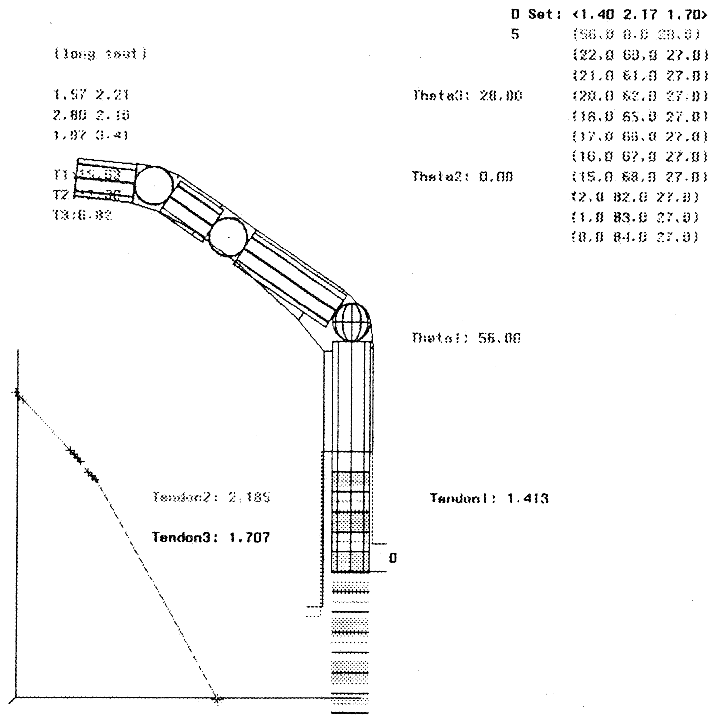


Figure 4: Finger Model in Position 1 of *Dset*

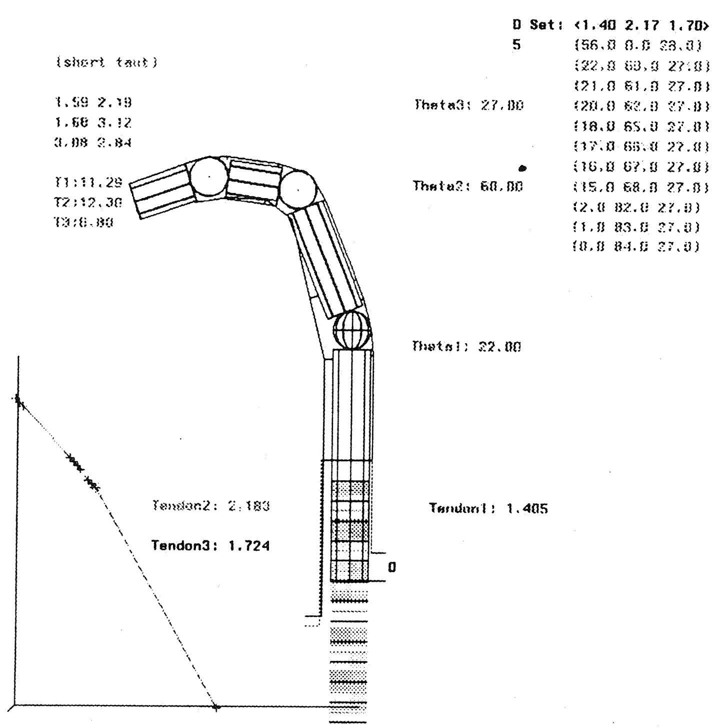


Figure 5: Finger Model in Position 2 of *Dset*

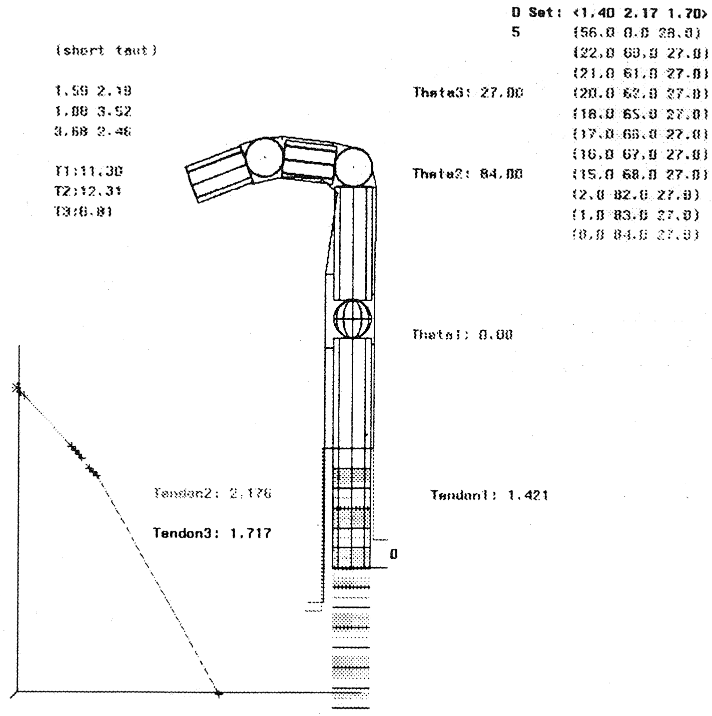


Figure 6: Finger Model in Position 3 of *Dset*


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