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# Biomechanical Design Principles Underpinning Anthropomorphic Manipulators

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## Abstract

The biomechanical design of an artificial anthropomorphic manipulator is the focus of many researchers in diverse fields. Current electromechanical artificial hands are either in the research stage, expensive, have patents, lack severely in function, and/or are driven by robotic/mechanical principles, which tend to ignore the biological requirements of such designs. In response to the challenges addressed above this chapter discusses the potential of current technology and methods used in design to bridge the chasm that exists between robot manipulators and the human hand. This chapter elucidates artificial anthropomorphic manipulator design by outlining biomechanical concepts that contribute to the function, esthetics and performance of artificial manipulators. This chapter addresses joint stabilization, tendon structures and tendon excursion in artificial anthropomorphic manipulators.

**Keywords:** anthropomorphic, manipulator, biomechanics, design, mechanics, robotics

## 1. Introduction

In general, traditional mechanics and robotics have been the fundamental foundation for artificial hand/manipulator design. As a result, robotic and electro-mechanical manipulators lack the dexterity and anthropomorphism that comes from considering the physiological and biological aspects inherent in the human hand. This chapter looks at three key biomechanical inspired principles that directly influence artificial hand function and dexterity. These are:

1. Joint stabilization
2. Tendon structures
3. Tendon excursion

**Figure 1** below gives an example of one potential anthropomorphic manipulator employing the above-mentioned principles.



**Figure 1.**  
*Anthropomorphic approach toward artificial hand design.*

### **1.1 Paradigm shift in anthropomorphic manipulator design**

The very nature of human anatomy presents a unique challenge in the replication of the human hand. Mechanical engineering approaches rely on the expectation that the artificial hand design approach is quantifiable. The following reasons provided by [1] providing insight as to why mimicking the human body is not a straight forward process.

1. The boundaries of ligaments, tendons, and muscles are not easily definable.
2. Ligament, tendon, and muscle insertions differ from person to person.
3. Some tendons and ligaments possess non-linear characteristics that make measurement inaccurate.
4. Some human tissues have no measurable resting position.

For these reasons quantifiable methods are hard to realize. In reality, working in the space of anthropomorphic manipulator design becomes subject to engineer/designer best practice or previously knowledge. This reality often leads to this chapter, will express the value of a paradigm shift by exploring the biomechanical and physiological design principles that contribute to anthropomorphic manipulator design. The chapter concludes with a set of defined grasps that are a direct result of the design paradigm shift.

## 1.2 Current state

To this point in time, the human hand has been the “golden standard” of function, versatility and dexterity in grasping tasks as proven by the ongoing attempts to artificially recreate it [2]. Mimicking the qualities and properties of the human hand has always been a lofty and hard to realize goal, however, due to the current technological advancements of our age we are closer to achieve it than ever before. For these reasons this research is progressive, of great value and exciting. The ability of an artificial hand to function in an unmodified human environment directly relates to its capacity to function like the human hand. Traditional approaches to artificial hand design have been susceptible to ignore and/or omit the organic biological features of the human anatomy that are essential to hand function. Recent trends are tending toward artificial hand design that includes multidisciplinary viewpoints that consider more than just traditional mechanical principles.

In artificial hand design it is important to consider the Degrees of Freedom (DoF) the hand possesses. The DoF of a system is the number of independent parameters that define its configuration. The reviews [3, 4] describe some of the available electromechanical hands currently on the market [5–16]. Each review supports the general view that as the DoF of an artificial hand increases so does its anthropomorphism and function. Research into modeling the human hand claims that 24 DoF accurately represents the posture and movement of the human hand (including the wrist) [17]. There is consensus around this point with most literature agreeing that the human hand has between 21 and 26 DoF depending on whether you include or exclude the wrist [18]. The difference in DoF between studies can also be attributed to the DoF associated with the carpal bones of the hand and whether or not they are included.

Latter attempts at hand design employ the idea of bio-mimicry or an approach that is human inspired. The focus of these types of hands are on the tendinous structures actuating the hand and their synergies with ligaments, joints and actuators [4] approaches artificial hand design by mimicking the human bones and joints of the hand. Naturally, this makes for an esthetically pleasing design. In contrast to this approach a bulky unnatural looking wrist was implemented in the design and was recognized as required improvement [19] builds upon the idea of biomimicry by developing artificial tendinous structures that mimic the human hand and by improving the design of artificial thumbs. Their approach was esthetically pleasing and functioned well. Within their approach there was a new idea to incorporate joint capsules at each joint. Further studies [1] in the same year presented work on mimicking the mechanics and material properties possessed by the human hand and incorporating them into working artificial prototypes. The work presented herein emphasis the synergistic tendon networks, bone configuration, bone orientation, and joint development that are required in artificial hand design. It is expected that these types of approaches will increase in popularity and improve as the research climate and time allows.

## 2. Joint stabilization

The following section addresses the connection that exists between hand function and artificial ligament design. Firstly, it is important to understand how the bones of the human hand lay a foundation for the ligaments to layer on. The bones on which hand ligaments are inserted provide ligament pathways on which joint stabilization relies. Incorrect placement of ligaments severely effects the way a bone moves, transfers force and thus can drastically reduce the function of a hand. The bones of the human hand are essential to hand function, however, without the stabilizing ligaments and tendons they are of little use. Each joint of the hand has a series of ligaments that limit undesirable movement and protect the hand against excessive force. Hence, joint stabilization by virtue of the biological layers present in the human hand are integral to hand function.

Joint stabilization is integral to hand function; therefore, it is important to unpack the role and location of the ligaments responsible for finger joint stabilization and movement. In particular, the following section describes and defines the collateral ligament, the volar plate, and the annular ligament. Each ligament is then put in context by applying them to the design shown in **Figure 1**. We begin by explaining the collateral ligament and follow that by exploring both the volar plate and annular ligament.

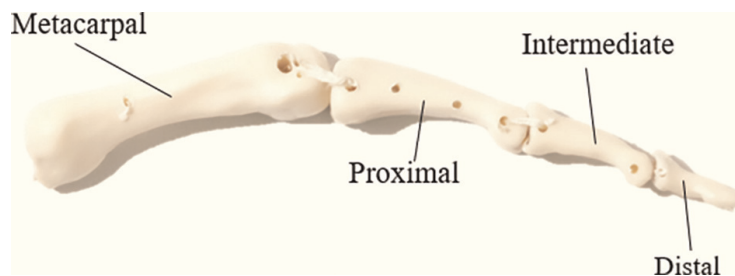
### 2.1 Collateral ligament

This section describes the artificial collateral ligament by defining suitable insertion locations of the ligament for each phalanx of the hand that optimizes the movement between adjacent bones. The collateral ligament acts as the primary stabilizer of phalanx joints and is responsible for connecting bones. Taking the index finger as an example we name and orient the bones of the finger in **Figure 2**.

Determining the insertion positions of the collateral ligament on the artificial proximal phalanx (**Figure 3**) is defined by two features. These features are: The phalanx length,  $L_P$ , and the centroid,  $c$ . the phalanx length,  $L_P$  is the summation of  $L_{BC}$  and  $L_{HC}$  while the centroid is found through the CAD software SOLIDWORKS using the mass property evaluation.

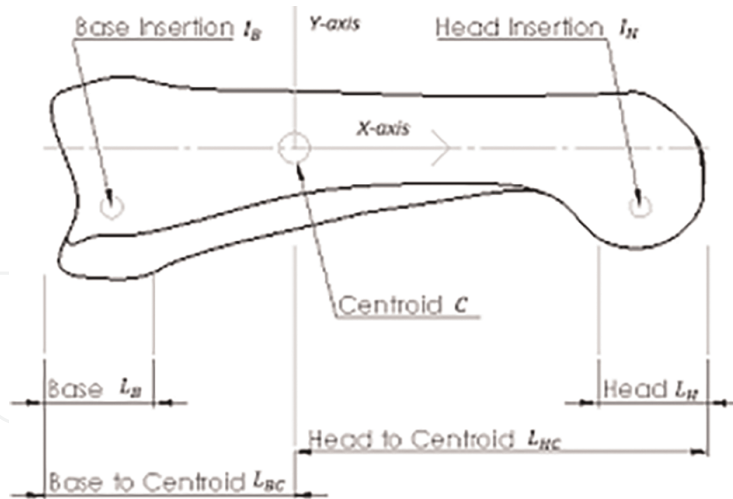
The coordinate system is established on the centroid of the phalanx. The phalanx length and the location of the centroid determine the ligament insertion locations  $I_H$  and  $I_B$ .  $L_B$  and  $L_H$  define the limits that bound the insertion locations. The coordination of the head insertion  $I_H$  and base insertion  $I_B$  are given by

$$I_H = (x, y) = ((L_{HC} - L_{HI}), (y < 0)) \quad (1)$$



**Figure 2.**  
Index finger bone configuration and orientation.





**Figure 3.**  
Collateral ligament insertion points.

and

$$I_B = (x, y) = ((-L_{BC} + L_{BI}), (y < 0)) \tag{2}$$

Where  $L_{BI}$  and  $L_{HI}$  are determined by a ratio of the total phalanx length,  $L_P$ , that is still acceptable for correct bone interaction between each phalanx. The values for  $L_{BI}$  and  $L_{HI}$  are determined by a joint motion test. Insertion points are designed and modeled at distances between 3 mm and 8 mm from each end of the involved phalanx. Joint motion is quantified by a rating between one and three. Where one represents a good range of motion and three represents a poor or severely lacking range of motion. Any insertions below 3 mm or above 8 mm do not provide any range of motion and do not add contribute to the motion of the joint. (Values for  $L_{BI}$  and  $L_{HI}$  are found by dividing the insertion distance by the phalanx length). As shown in Eqs. (1) and (2) the location of the insertion in the vertical direction is governed by the variable,  $y$ . If,  $y = 0$  the insertion is located along the  $x$ -axis. If  $y < 0$  the insertion is located below the  $y$ -axis. If the insertion is governed by  $(\pm y)$  then it has two insertion points either side of the  $y$ -axis. The three insertion location conditions are expressed by the following equations:

Condition (1) is expressed by

$$(x, y) = ((L_{HC} - L_{HI}), (y = 0)) \tag{3}$$

Condition (2) is expressed by

$$(x, y) = ((L_{HC} - L_{HI}), (\pm y)) \tag{4}$$

Condition (3) is expressed by

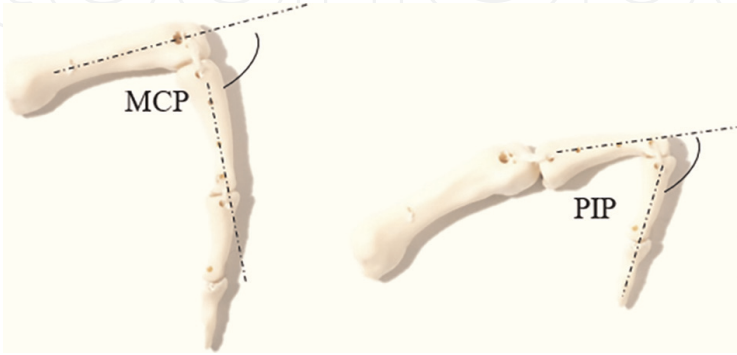
$$(x, y) = ((-L_{BC} + L_{BI}), (y < 0)) \tag{5}$$

For ease of application **Table 1** below outlines the conditions applicable to both the head and base of each phalanx.

Any major variance from the values and conditions listed in this table are detrimental to the joints range of motion and its stabilization. Through this method

	Metacarpal		Proximal		Intermediate		Distal	
	Head	Base	Head	Base	Head	Base	Head	Base
Condition 1			x		x			
Condition 2	x							
Condition 3				x		x		x

**Table 1.**  
*Insertion location conditions assigned to each phalanx.*



**Figure 4.**  
*MCP and PIP joints including their ranges of motion.*

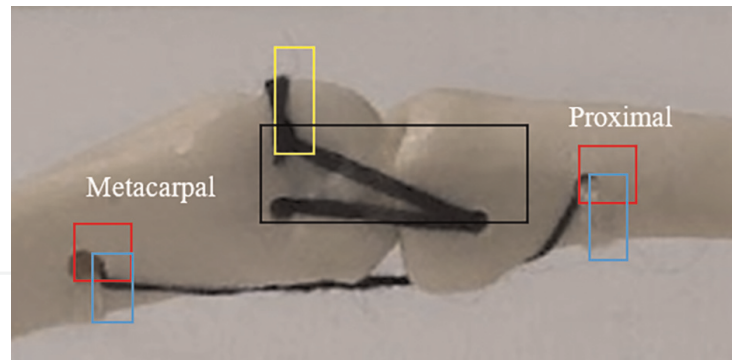
collateral ligament insertion is generalized for all artificial hand design. The geometry of the bones in the hand compliment the collateral ligaments at each bone-ligament interface. Collateral ligament placement determines joint function and therefore hand function. Bone surfaces are congruent and possess depressions or protuberances that give clues to ligament insertion locations. The bone surfaces also permit human like range of motion at each joint. **Figure 4** shows the resulting range of motion,  $\mu$  for the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints.

The resulting range of motion of the artificial MCP and PIP joints sit within two degrees measurement of their natural human counterparts, meaning digit function and dexterity are maximized. The collateral ligaments are vitally important to hand function, however, as recognized at the beginning of this section there are three main ligaments responsible for joint stabilization. The next section will look at the remaining ligaments which are the volar plate and the annular ligament.

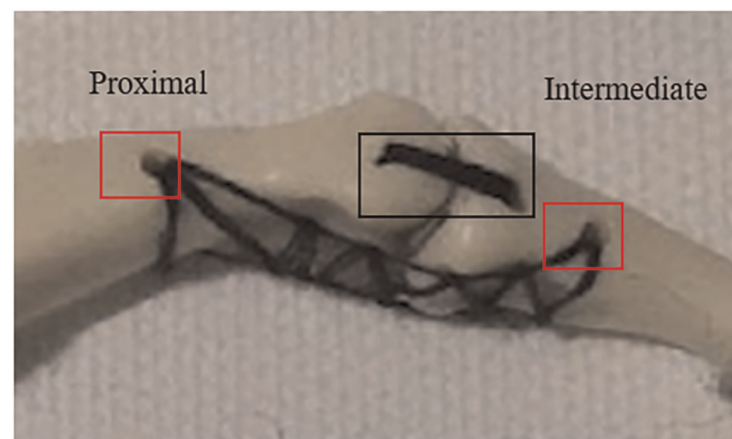
## 2.2 Digit joints

The collateral ligament represents one of the three stabilizing ligaments of the joints of the fingers. This section will describe the role and placement of the volar plate and the annular ligaments with respect to the previously described artificial collateral ligament. The combination of these three ligaments make up the joints of the finger and work in harmony to provide the function and dexterity of the hand. The collateral ligament provides lateral stability and is represented in the black box **Figure 5**. The insertions are achieved via an extruded cut through the proximal phalanx and abide by the conditions stated in **Table 1**.

In synergy with the collateral ligament is the volar plate. The volar plate functions to protect the fingers against hyperextension with its insertion points highlighted in the red boxes of **Figure 5**. These insertions are found on the palmar side of the



**Figure 5.**  
 The stabilizing ligaments of the MCP joint.



**Figure 6.**  
 The stabilizing ligaments of the PIP joint.

metacarpal head and the palmar side proximal base. A properly function volar plate limits rotation about the joint and absorbs excessive force placed on the joint in unwanted directions. It can most easily be thought of as a limiter of unwanted movement.

An artificial sagittal band is incorporated into the design of the artificial hand (yellow box of **Figure 5**). Although the sagittal band and the collateral ligament share insertion locations their functions are very different. The sagittal band creates a pathway for the extensor tendon responsible for force transferral and finger extension. It also eliminates transverse tendon slippage. In addition to the sagittal band the hand incorporates annular ligaments. These ligaments share insertions with the volar plate. These ligaments are light in color but outlined by blue boxes in **Figure 5**. The combination of these ligaments allows abduction/adduction and flexion/extension at the MCP joint. The lateral movement in the MCP joint is limited through the placement and angle of the collateral ligaments while rotation is limited by the volar plate. If designed correctly the congruence provided by the geometry of the bones allows smooth movement through the flexion and extension movements of the joint. The concave/convex relationship between the bones also allows abduction and adduction.

The PIP joint (**Figure 6**) connects the intermediate and proximal phalanges. The PIP joint on its own is a planar manipulator capable of only flexion and extension and just like the MCP is stabilized by the collateral ligament (black box **Figure 6**).

The palmar side of the PIP joint houses the volar ligament. The insertion points of this ligament are outlined in **Figure 6** by red boxes. This ligament functions to protect



the joint from hyperextension and shares an insertion with the annular pulleys. The PIP joint provides simple planar movement that allows the hand to grasp and manipulate objects with precision and force. Bone geometry and size naturally limits the unwanted motion inherent in the joint, allowing a natural moving and anthropomorphic esthetic.

The final joint of the finger is the distal interphalangeal (DIP) joint. This joint connects the intermediate and distal phalanges. The DIP joint is a copy of the PIP joint described above.

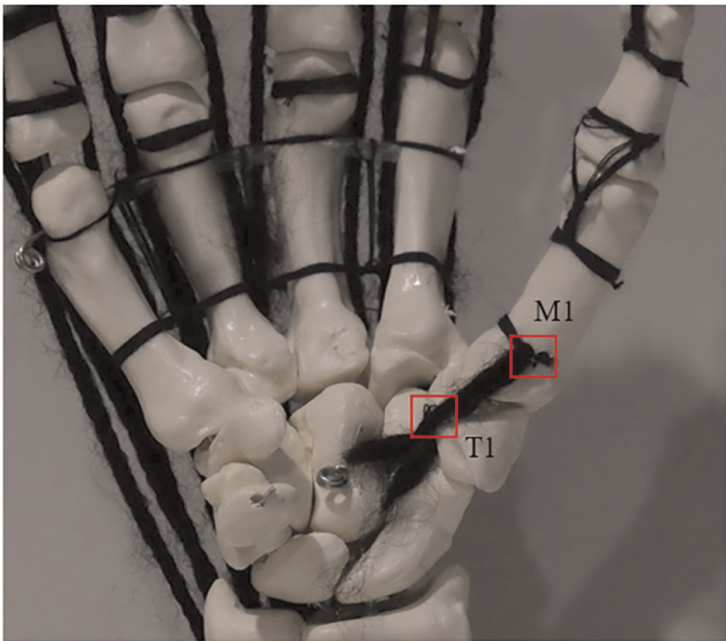
### 2.3 The carpometacarpal joint

The thumb has traditionally been an incredibly hard appendage to mimic and replicate artificially. On its own the thumb is the single largest contributor to hand function and dexterity. It is what sets humans apart from the rest of the animal kingdom. With these sentiments in mind it is important to consider the biomechanical makeup of the thumb and incorporate it within the design process.

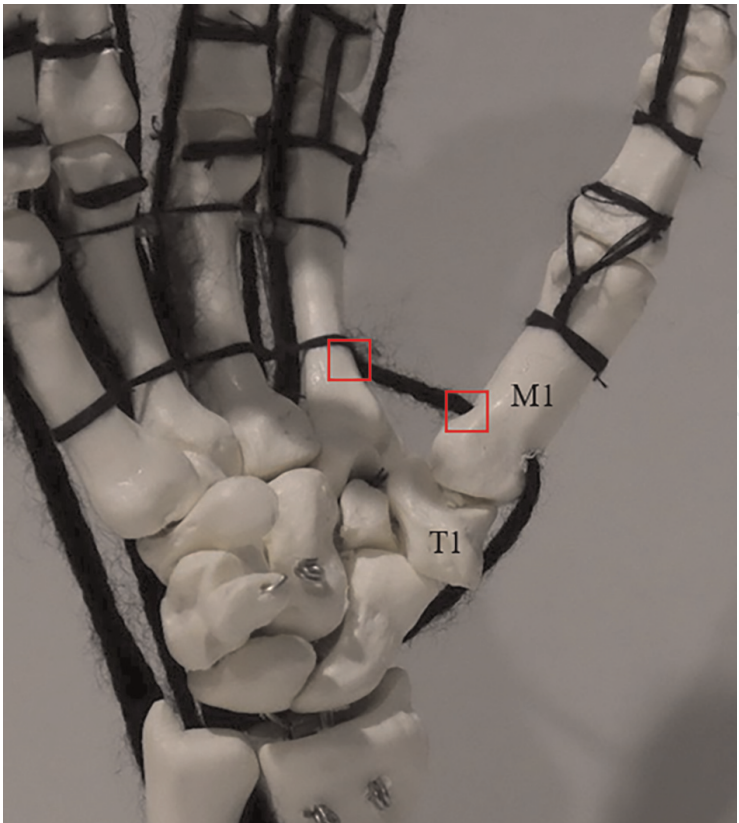
The Carpometacarpal (CMC) joint of the thumb provides the hand with complex multi-axial movement. The reason for this is the complex geometry of the trapezium bone and its relationship with the metacarpal of the thumb. Artificial ligaments provide stabilization for the CMC joint of the thumb on the artificial hand. The five artificial ligaments are based on the human counterparts and are described below.

The Anterior Oblique ligament (**Figure 7**) is the first of the stabilizing ligaments of the thumb. T1 represents the trapezium bone while M1 indicates the metacarpal bone of the thumb. The anterior oblique ligament functions to limit unwanted movement that would cause the CMC dislocation. The ligament connects the metacarpal bone and trapezium bones. The insertion points are highlighted in red.

In addition to the anterior oblique ligament there is the second stabilizing ligament shown in **Figure 8**. This ligaments function is to stabilize the joint and to limit the movement between the thumb and the palm. As shown, this ligament is inserted near



**Figure 7.**  
*The anterior oblique ligament of the CMC joint. (palmar view).*



**Figure 8.**  
*CMC joint and its artificial ligaments (dorsal view).*

the base of the index metacarpal and the thumb metacarpal (insertions are highlighted in red).

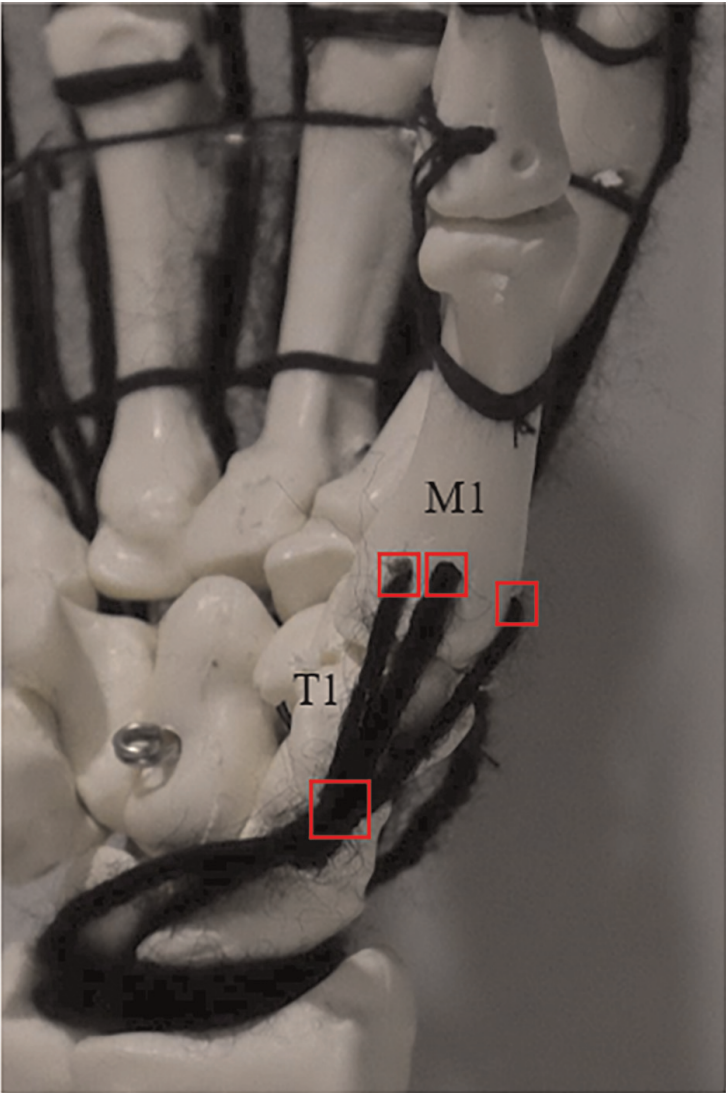
Ligaments three, four and five are artificial replications of the dorsal deltoid shaped ligaments. These are also stabilizing ligaments and are named the dorsal radial ligament, the dorsal central ligament and the posterior oblique ligament. These ligaments share an insertion on the trapezium bone and are connected the surface of the metacarpal bone of the thumb. Each ligament inserts at different points along the metacarpal surface to provide the thumb with a considerable range of motion. All three ligaments contribute to allowing and restricting of movement within their respective three-dimensional spaces. These three ligaments are shown **Figure 9** and are highlighted in red.

The previously mentioned ligaments work in synergy to stabilize the thumb joint and create the base on which the CMC joint relies for function. Along with the complex geometry of the bones at the CMC join these ligaments are responsible for the complex multi-axial movement of the thumb.

This and previous sections have conveyed one possible approach to joint stabilization in artificial anthropomorphic manipulators. The following section will now move into the actuation of these joints by tendons.

### 3. Tendinous structures

Movement of the human skeleton originates from the transferral of forces between it and its associated tendon/muscle. This is especially important for understanding hand movement as each minute movement can be attributed to the actuation of a



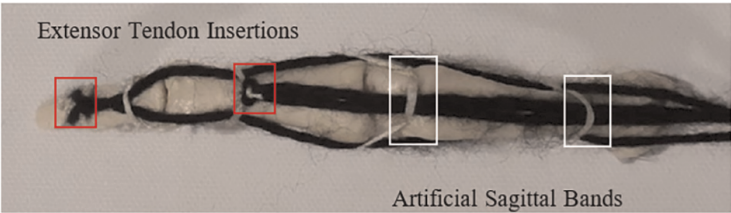
**Figure 9.**  
*The CMC joint and its artificial dorsal deltoid shaped ligaments (palmar/lateral view).*

muscle or tendon. This section approaches the biomimicry of this process by separating the complex movement of the hand into two. Firstly, the tendons that control the fingers and secondly, the tendons that control the thumb.

### 3.1 Finger tendons

The finger has two primary movements and two minor movements. The primary movements are flexion and extension. The extensor tendon straightens the finger while the flexor tendons bend the finger. The minor movements of the finger are called adduction and abduction. These movements are induced by the contraction and elongation of the palmar interossei muscles. In order to understand the movements of these tendons and how they transfer force into the bones we need to look at their insertion points. We start by outlining the insertions of the extensor tendon. The first insertion is on the distal phalanx and the second is on the intermediate phalanx. These positions are highlighted in the red boxes in **Figure 10**. After its insertion on the intermediate phalanx the extensor tendon splits. This split helps to engage the finger in abduction and adduction. Artificial sagittal bands control the extensor tendon pathway as shown in **Figure 10** (white boxes) and prevent transverse slipping of the





**Figure 10.**  
*The pathway and insertion points of the extensor tendon. (Dorsal view).*

tendon. The flexion of the fingers in the hand are actuated by the Flexor Digitorum Profundus (FDP) tendon.

These FDP tendons traverse the palmar side of the hand and insert at the distal phalanx of each finger. The following section will outline the tendons of the thumb responsible for the thumb function, movement and anthropomorphism.

### 3.2 Thumb tendons

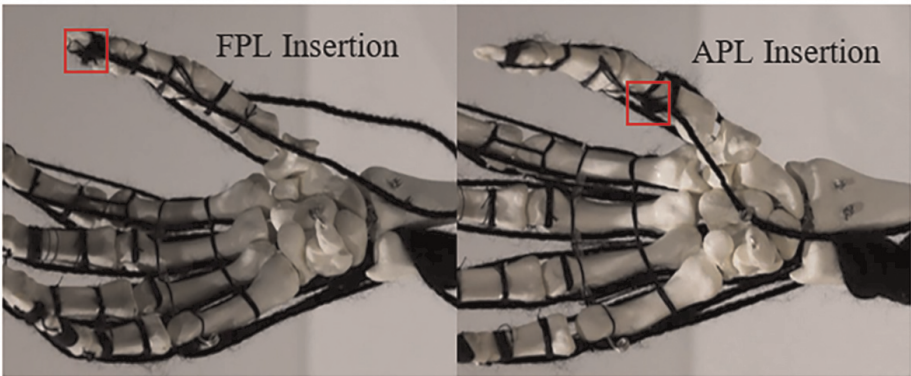
The thumb is a masterpiece of mechanical complexity and is capable of producing complex multi-axial movement. It is essential to understand its basic anatomy and function. Four main tendons are responsible for this movement.

- The Abductor Pollicis Longus (APL).
- The Flexor Pollicis Longus (FPL).
- The Extensor Pollicis Brevis (EPB).
- The Extensor Pollicis Longus (EPL).

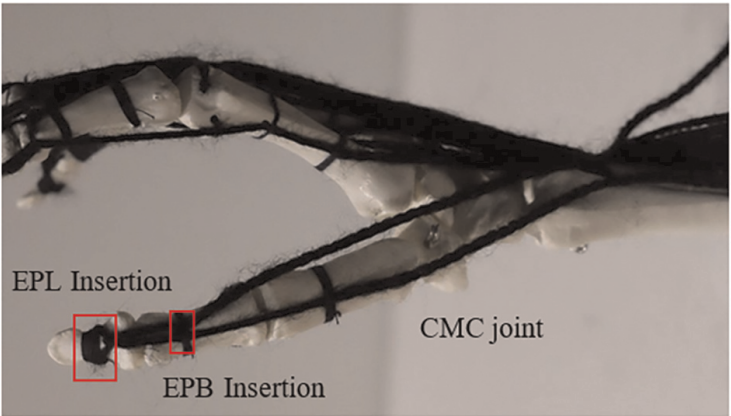
The design and function of these tendons are described in the next section.

The artificial FPL shown in **Figure 11** (left-hand side) is channeled through the carpal tunnel and directed toward the base of the thumbs distal phalanx where it is inserted. The APL also shown in **Figure 11** (right-hand side) inserts into the thumbs metacarpal on the radial side and provides the thumb with abduction at the CMC joint.

**Figure 12** (red boxes) below shows the insertion points of the EPB and the EPL. The EPB inserts into the thumbs proximal phalanx. This tendon is responsible for



**Figure 11.**  
*The artificial FPL and APL insertions of the thumb. (Palmar view).*



**Figure 12.**  
*The artificial EPL and EPB insertions of the thumb.*

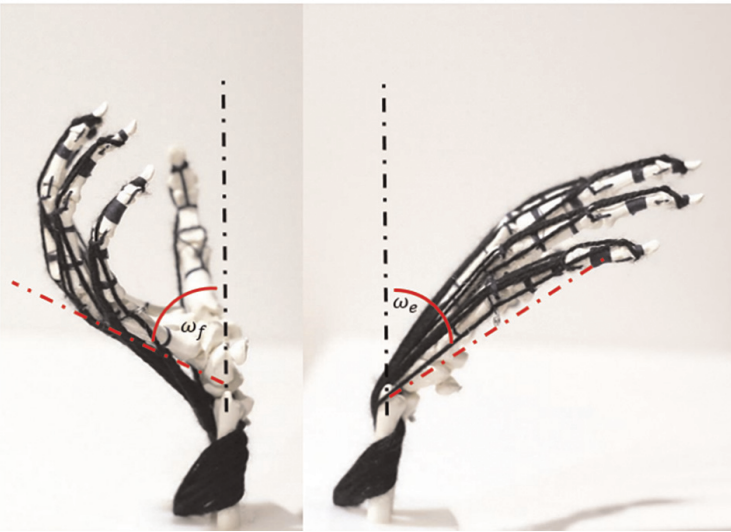
extension and abduction of the thumb at the CMC joint. The EPL is channeled through the rear of thumb and inserts at the tip distal phalanx. The EPL allows complete thumb extension whereas the PB can only provide partial extension.

It is through a complex synergy that the above-mentioned tendons provide the complex multi axial movement including flexion, extension, and circumduction.

**4. Tendon excursion**

Tendon excursion is often thought of as a limiting factor in electromechanical hand design. Tendon excursion is the displacement an artificial tendon experiences when the associated muscle/actuator contracts and induces tensile forces on it. Tendon excursion is can effect hand movement negatively.

For example, wrist movement induces tendon excursion on all the FDP tendons of the fingers. This can be seen in the natural flexion of the fingers during wrist extension and their natural extension during wrist flexion (**Figure 13**).



**Figure 13.**  
*Tendon excursion in the FDP of each finger induced by wrist movement.*



The angles  $\omega_f$  and  $\omega_e$  represent the magnitude with which the wrist joint is in flexion or extension respectively.  $\omega = 0$  is located vertically upward from the forearm bones and is measured from the pivot point of the wrist to the metacarpal creating the largest angle from the equilibrium point. In this case measurements are taken from the metacarpal of the little finger. Let us take the artificial FDP flexor tendon of each digit as an example. We can write a set of tendon displacements with respect to the wrist angle. Let,  $\omega_f$  represent wrist flexion for any  $\omega > 0$ . We can write

$$\omega_f = \{d_{Fi} d_{Fm} d_{Fr} d_{Fl} d_{Ft}\} \quad (6)$$

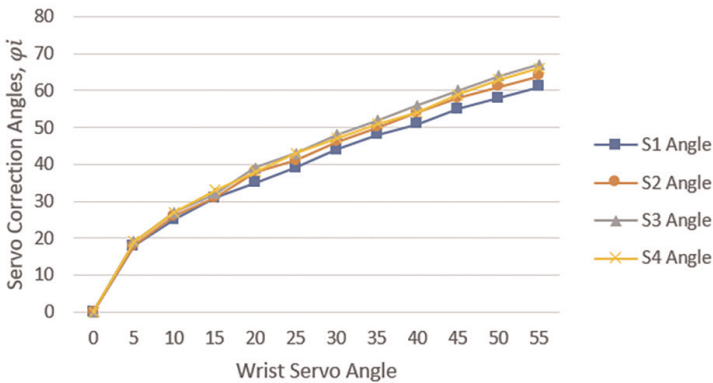
Where,  $d$  is the displacement of the tendon in mm and the subscripts  $i, m, r, l$  and  $t$  are the index, middle, ring, little, and thumb digits respectively. The subscript,  $F$ , represents the flexor tendon and in the case of the thumb,  $d_{Ft} = \{d_{Ft1} d_{Ft2}\}$ . Where,  $d_{Ft1}$  and  $d_{Ft2}$  are artificial replications of the the APL and FPL (**Figure 11**) tendons respectively.

The effect of tendon excursion can be quantified by measuring the elongation/displacement flexor tendons while the wrist is moving. After measuring the artificial FDP displacement each finger was displaced by over 10 mm. A 10 mm displacement represents more than 50 percent of the fingers total motion, thus, tendon excursion cannot be ignored. In a similar manner the effect of tendon excursion on the thumb is too large to ignore, therefore we look to the following section as one solution to manage the unwanted effects of tendon excursion.

The source of displacement for each artificial tendon stems from its actuator, therefore, solutions can be found by adjusting the tendons actuator to account for the unwanted tendon excursion. Let us assume an anthropomorphic manipulator we have a series of four servomotors actuating four artificial FDP tendons. A servomotor correction factor can be implemented within the control scheme which considers the wrist angle. The correction factor allows the wrist induced excursion to meet equilibrium with the individual finger servomotors during wrist movement using:

$$e = \left( \frac{\pi R}{180} \right) \times \varphi_i \quad (7)$$

Where,  $R$  is the servo horn radius and  $\varphi_i$  is the angle of the servo horn. By so doing, the servomotor angles for each digit can be plotted against the wrist angle,  $\omega$  at any given time.



**Figure 14.**  
Servomotor correction angles for wrist movement induced tendon excursion in the fingers.

The excursion correction angles displayed in **Figure 14** shows how servomotor angles change with respect to wrist position.

Including these types of correction tables into the control schemes of all electromechanical anthropomorphic hands is trivial but important for hand function and control.

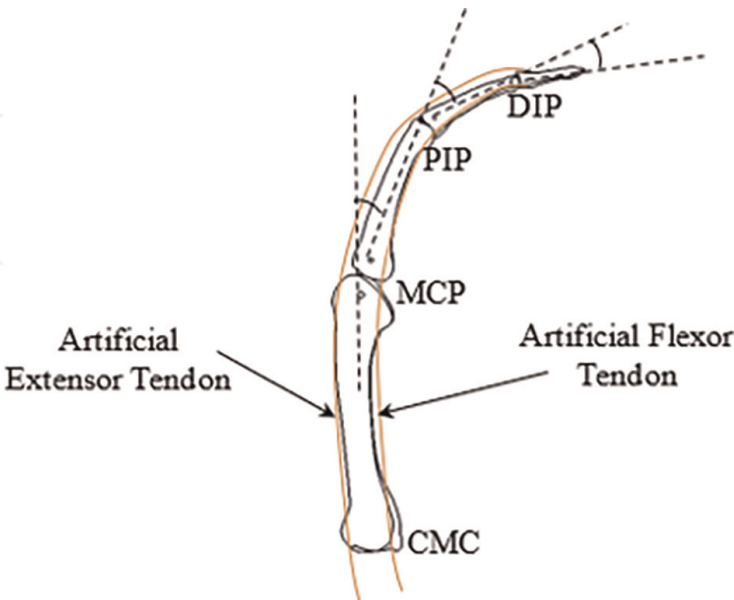
5. Defining grasps

Artificial tendons provide movement in the hand. These tendons induce rotations about the joints of the digits. Assignments are shown in **Table 2**.

**Figure 15** shows the joint angles of each phalanx with respect to each previous joint. Using the relationship between tendon displacement and joint angles we can define a grasp type.

Digit	Tendon label <i>i</i>	Digit movement
Thumb	1 and 6	Tendon 1 is for flexion and extension
Index finger	2	Tendon 6 is for opposition and reposition
Middle finger	3	Flexion and extension
Ring finger	4	Flexion and extension
Little finger	5	Flexion and extension

**Table 2.**  
*Tendon arrangement for finger actuation.*



**Figure 15.**  
*Artificial hand finger tendon network and the associated joint angles.*

For simple tendon networks composed of 3 pulleys in a digit, the tendon extension,  $e_i$ , is a linear function of the change of the joint angles  $\Delta\theta_{i1}$ ,  $\Delta\theta_{i2}$  and  $\Delta\theta_{i3}$ . Therefore, tendon extension can be expressed as

$$e_i = \sum_j r_{ij} \Delta\theta_{ij} \tag{8}$$

Where,  $r_{ij}$ , is a measure of the pulley radius at the  $j$ -th joint ( $j = 1, 2, 3$  for  $i$  where  $i = 1, 2, \dots, 5$  and  $j = 1$  for  $i = 6$ ).

The extensions shown above can be used to determine grasp strength. Each tendon tendons is connected to individual servomotors to actuate digit movement. The artificial hand has six servomotors, one for each finger and two for the thumb. A grasp type in this context is defined as

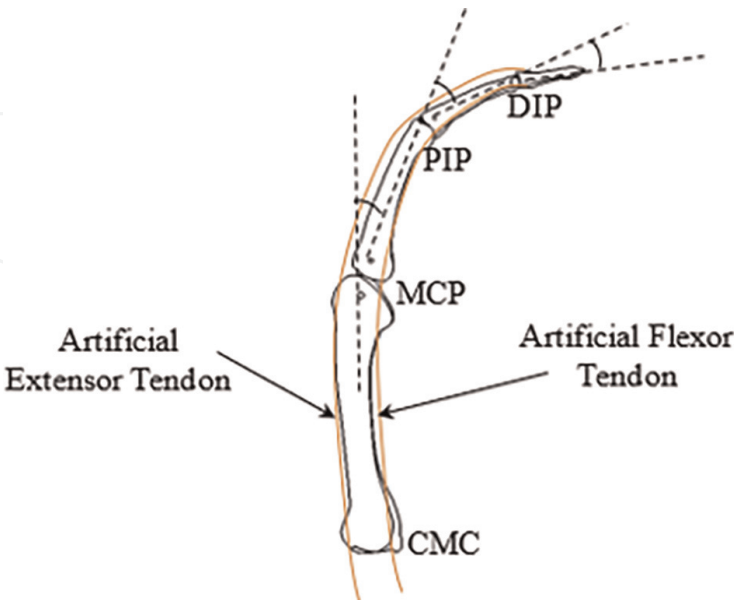
$$\phi = [\varphi_1 \varphi_2 \varphi_3 \varphi_4 \varphi_5 \varphi_6 \ c]^T \tag{9}$$

Where,  
 $c = \{1, \text{for force closure grasping or } 0, \text{for form closure grasping}$

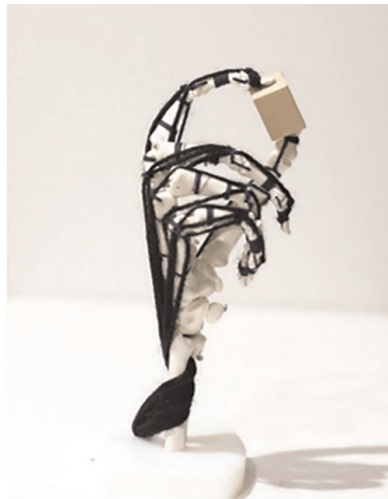
when  $\varphi_i$  ( $\forall i$ ) equals the pre-set maximum servomotor angle,  $\varphi_i^{max}$  the digit is in complete flexion. Otherwise, it is in complete extension (that is  $\varphi_i = 0$  or  $\varphi_i^{min}$ ).

A physical representation of Eq. (9) is shown in the working principle of finger actuation displayed below in **Figure 16**.

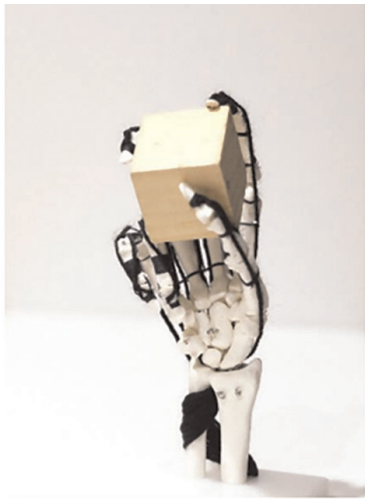
In continuation of the rule established above **Figure 17** below demonstrates the four common grasp types and their definitions. The grasps shown are:



**Figure 16.**  
*Digit extension and flexion due to the servo motor angle.*



Palmar pinch grasp  
 $\boldsymbol{\varphi} = [\varphi_1 \ \varphi_2 \ \varphi_3^{max} \ \varphi_4^{max} \ \varphi_5^{max} \ \varphi_6 \ 1]^T$



Tripod grasp  
 $\boldsymbol{\varphi} = [\varphi_1 \ \varphi_2 \ \varphi_3 \ \varphi_4^{max} \ \varphi_5^{max} \ \varphi_6 \ 1]^T$



Power grasp sphere (3 Finger) grasp  
 $\boldsymbol{\varphi} = [\varphi_1 \ \varphi_2 \ \varphi_3 \ \varphi_4^{max} \ \varphi_5^{max} \ \varphi_6 \ 0]^T$



Power sphere grasp  
 $\boldsymbol{\varphi} = [\varphi_1 \ \varphi_2 \ \varphi_3 \ \varphi_4 \ \varphi_5 \ \varphi_6 \ 0]^T$

**Figure 17.**  
*Grasp types performed by the artificial hand and their definitions.*

- Palmar pinch.
- Tripod grasp.
- Power grasp sphere (3 finger).
- Power grasp.

In the case of objects where one of its dimensions are much larger than the other a tip pinch grasp or a power grasp is appropriate (**Figure 18**).



Tip pinch grasp  
 $\varphi = [\varphi_1 \ \varphi_2 \ \varphi_3^{max} \ \varphi_4^{max} \ \varphi_5^{max} \ \varphi_6 \ 1]^T$



Power grasp  
 $\varphi = [\varphi_1 \ \varphi_2 \ \varphi_3 \ \varphi_4 \ \varphi_5 \ \varphi_6 \ 1]^T$

**Figure 18.**  
*Tip pinch and power grasp examples and definitions.*

## 6. Conclusion

This chapter has outlined artificial anthropomorphic manipulator design by providing potential solutions to the challenges of mimicking the biomechanics of the human hand. Our current reality is that mechanical design considerations have been prioritized over bio-mimicry, this chapter approaches this challenge with a perspective that is refreshing and valuable. The biomechanical concepts explored in this chapter are vital in the design of artificial anthropomorphic manipulators. These biomechanical concepts contribute to the function, esthetics and performance of the manipulator and should not be ignored. It is expected that as joint stabilization, tendon structures and tendon excursion become prioritized that we will reach a level of anthropomorphism not realized in any other period in the history of artificial hand design.

### Nomenclature, abbreviations and symbols

MCP	Metacarpophalangeal
PIP	Proximal Interphalangeal
DoF	Degrees of Freedom
DIP	Distal Interphalangeal
CMC	Carpometacarpal
FDP	Flexor Digitorum Profundus
APL	Abductor Policis Longus
FPL	Flexor Policis Longus
EPL	Extensor Policis Longus
EPB	Extensor Policis Brevis




$L_p$	Phalanx length
$I_H$	Head insertion
$I_B$	Base insertion
$L_{HC}$	Head to centroid length
$L_{BC}$	Base to centroid length
$L_B$	Base Length
$L_H$	Head Length
$L_{BI}$	Percentage of phalanx length
$L_{HI}$	Percentage of phalanx length
$e_i$	Tendon extension
$\omega_f$	Wrist flexion
$\omega_e$	Wrist extension
$\omega_f^{max}$	Maximum wrist flexion
$\omega_e^{max}$	Maximum wrist extension
$\varphi_i$	Servo horn angle
$\varphi_i^{max}$	Maximum servo horn angle
$r_{ij}$	radius of pulley
R	servo horn radius
T1	Trapezium bone
M1	metacarpal bone
e	tendon displacement
c	centroid/force-form closure
d	displacement
i	Index finger
m	Middle finger
r	Ring finger
l	Little finger
S1–S4	Servo motors

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