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Biomechanical Concept Design of Artificial Human Hand

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Abstract

This work is focused on the design parameters and activity of artificial human finger for seven grips. At first, obtained the ideal kinematics of human fingers motion by analyzing the grips video which were recorded using a single digital camera recorder fitted on a tripod in sagital plane while the hand is moving. Special motion analysis software (Dartfish) the finger joint angles were studied using the video recording. Then the seven grips were modeled using static torque analysis, which calculates the amount of torque applied on the fingers joint grip depending on the results of the kinematic analysis. The last step of the work was to design the actuator (Muscle Wire) of artificial finger for the seven grips in a simple design approach for artificial finger actuated by (Muscle Wire).

Keywords: *kinematic analysis, human hand, dartfish, grips, muscle wire.*

1. Introduction

Many people lose the use of one of their hands, either through accident or birth defect. Although there are many solutions for a missing appendage, there are very few that give the user the same freedom of movement and control as a real hand. Robotic hands have been researched for the past four decades, many of which do not give as many degrees of freedom as a human hand [1]. The hand's functional uniqueness has been recognized and discussed extensively in the literatures. This work attempt to make simple design for the human finger that would facilitate the designing of prosthetic hand, this design depended on the kinematics analysis that calculated by using a special motion analysis program (dartfish), and these results used to evaluate the static torque analysis of the human finger in different grip .The actuator of this finger was muscle wire (Shape Memory Alloy) which designed depending the static torque analysis.

The purpose of the study to overcome the shortcomings of conventional prostheses by utilizing a biomimetic (i.e., life-like) approach to prosthetic hand design. This involves Attempt to design a biomimetic finger that facilitate in designing a prosthetic hand which give the amputee that loss their hand new chance, Calculate the kinematic analysis and the static torque analysis for the human hand in different grips, Utilization of the smart materials (Shape memory alloy) that work as artificial muscle. The results of this work could be used as standardized values for designing the prosthetic finger by multiplying it with actual force (change from one to another) that acting on the finger during performance the grips.

2. Anatomical Structure of Human Hand

The basic hand bones consist of the carpals, metacarpals, and phalanges. The carpal bones form the wrist and consist of eight bones arranged in two rows of four. The metacarpals form the palm area of the hand and consist of five long bones that radiate from the carpal bones as shown in Fig. (1). finally, the phalanges form the fingers of the hand. There is a proximal phalanx, a middle phalanx, and a distal phalanx for each finger [2]. The human hand has about 34 muscles that control it, which are classified into those outside of the hand (extrinsic muscles) and those that are within the hand (intrinsic muscles). Though the extrinsic muscles are located in the forearm, they transmit their force through tendons attached to the hand [3]. The median and ulnar nerves are the major nerves of the hand, which run the length of the arm in order to transmit electrical impulses to and from the brain to create movement and sensation. The median nerve is mainly responsible for muscles associated with wrist and finger flexion while the ulnar nerve is responsible for the rest of the muscles (all of the intrinsic muscles) in the hand [4].

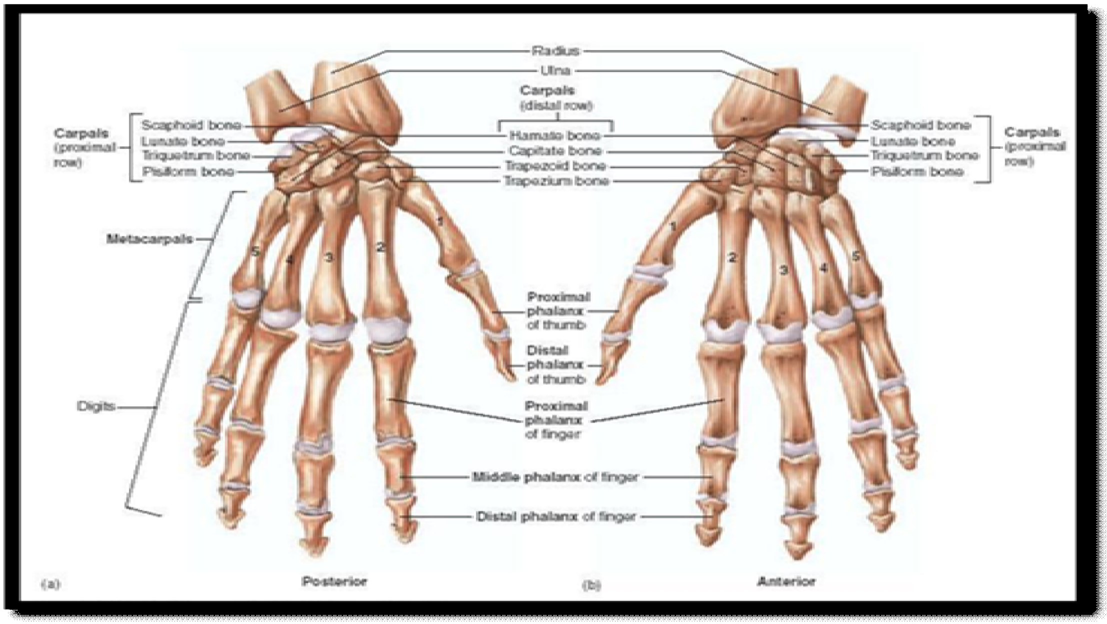


Fig.1. Bones of the Hand [5].

3. Biomechanics of the Hand

One may simplify things by thinking of the hand as fifteen joints, each of which is restricted to its own type of movement. These types of movement can be referred to as degrees of freedom as shown in Fig.2. the nine interphalangeal joints can be described as only having one degree of freedom: flexion-extension. The five metacarpophalangeal joints, however, have two degree of freedoms: flexion-extension and abduction-adduction (i.e. spreading fingers apart). The thumb is a little bit more complicated, with the base of the thumb having an extra two degree of freedoms when compared to the other fingers. And finally, the wrist itself has six degree of freedoms. Using this fifteen joint, one can approximate all of the possible movements of the human hand [6].

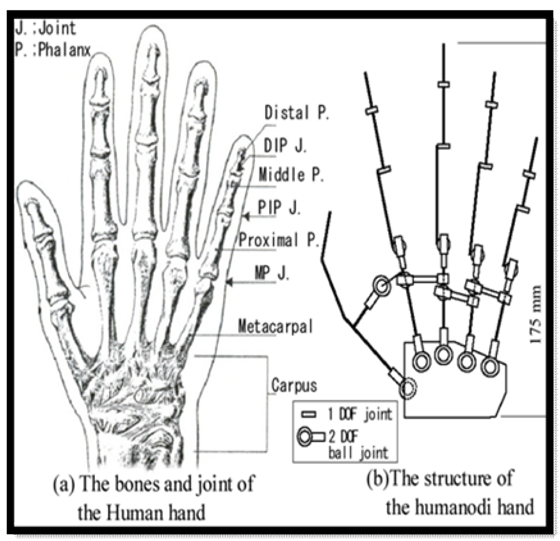


Fig.2. (a): The Bones and Joint of Human Hand (b) The Structure of the Humanoid Hand [7].

4. Design of the Biomimetic Finger (Index Finger)

4.1. Geometric Parameters of the Finger

The dimensions of the index finger (Length,breadth,depth and mass) are illustrated in the table(1).

Table 1,
Dimensions of the Index Finger [2].

Phalanx	Length (mm)	Breadth (mm)	Depth (mm)	Mass (g)
28.6	20.0	20.0	42.5	Proximal
9.6	17.5	19.0	28.125	Middle
4.7	13.84	16.6	22.5	Distal

4.2. Actuation Mechanism

A hybrid actuation mechanism is proposed where the Metacarpaphalengial and Phalengialinterpha joints are tendon-driven (muscle wire) and the Distalinterphalengeal joint is passively connected to the Phalengialinterphalengial joint by a pulley mechanism. The muscle wire formed a special metals undergo changes in shape and hardness when heated or cooled and do so with great force. Muscle wires pull with a surprisingly large force (capable of lifting thousands of times their own weight) and move silently with a smooth, life like quality. They can be heated directly with electricity and can be used to create a wide range of motions, operating quickly and with precise controllability [8].

4.3. Kinematic Architecture

The biomimetic finger consists of three links corresponding to the three phalanges of the human finger. The finger is equipped with three active degrees of freedom two at the metacarba phalengial joint and one at the phalengialinter phalengial joint and a passive degree of freedom at the distalinterphalengial joint. Furthermore, these joint center locations remain fixed along the entire range of motion of the phalanges [9]. Transposing these features to biomimetic model, fixed axes of rotations were implemented at the head of the phalanges; for the distalinter phalengial and phalengialinterphalengial joints, by modeling them as revolute hinge joints see Fig.(3). In these joints, the rotation occurs about a fixed shaft common to the head of the proximal phalanx and the base of middle phalanx for the phalengial interphalengial joint and the head of the middle phalanx and the base of the distal phalanx for the distalinterphalengial joint. The two degrees of freedom articulation of the metacarbaphalengial is modeled using a universal ball joint, which mimics the biaxial nature of the human finger's metacarbaphalengial joint [2].

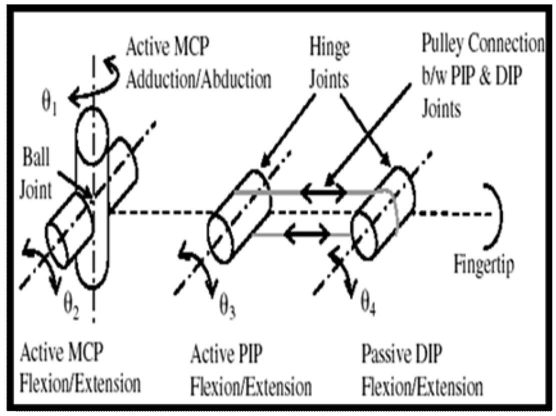


Fig.3. Finger Kinematic Architecture [2].

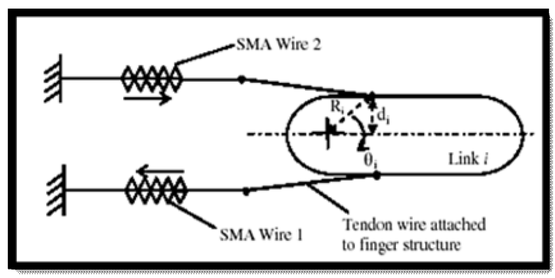


Fig.4. (Shape Memory Alloy) Wire Driven Agonist-Antagonist Tendon Pairs for Link *i* [2].

4.4. Finger Kinematics

A kinematic analysis of the finger is carried out in order to determine the relationship between the angular position of each joint and the required muscle wire contraction/elongation. The finger was modeled as a robot fixed to the palm. To evaluate the angles of each joint of finger at the seven grips, digital camera was used to perform this function and then the angles for each phalanx are calculated using special motion analysis program *(Dartfish)*. If the contracting muscle wire that causes clockwise rotation (flexion) is denoted as wire 1 and the opposing SMA wire is referred as wire 2, as shown in Fig.(4), then, at actuation, the lengths l_{1i} and l_{2i} of wires 1 and 2 are related to the joint angle *I* by the following equations [2]:

$$l_{2i} = \pm l_{2o} + R_i(\theta_{oi} - \theta_i) \quad \ldots(1)$$

$$l_{1i} = \pm l_{1o} + R_i(\theta_{oi} - \theta_i) \quad \ldots(2)$$

where θ_i : angle of joint i

4.5. Mathematical Model of Hand Grips

The model is a representation that could be understood, even though such representations may require gross simplifications and assumptions. By comparing a model's behavior with the actual behavior of the system, will obtain further insight in to how components of the system function and are coordinated to achieve desired outcomes. Each time a model doesn't predict a system's behavior correctly, could rationally change certain parts of the model, thus gaining insight into the complex nature of the real system, and the human biomechanical system is very complex [10]. One major consideration in designing prosthetic hands is the ability to hold an object in a stable grasp. The joints torques that is sufficient to sustain such a grasp is evaluated for different finger configurations [2]. Seven grips were studied (cylindrical, lifting box, push button, hook, spherical, tip and key) Fig.(5),but cylindrical grip mentioned in details.

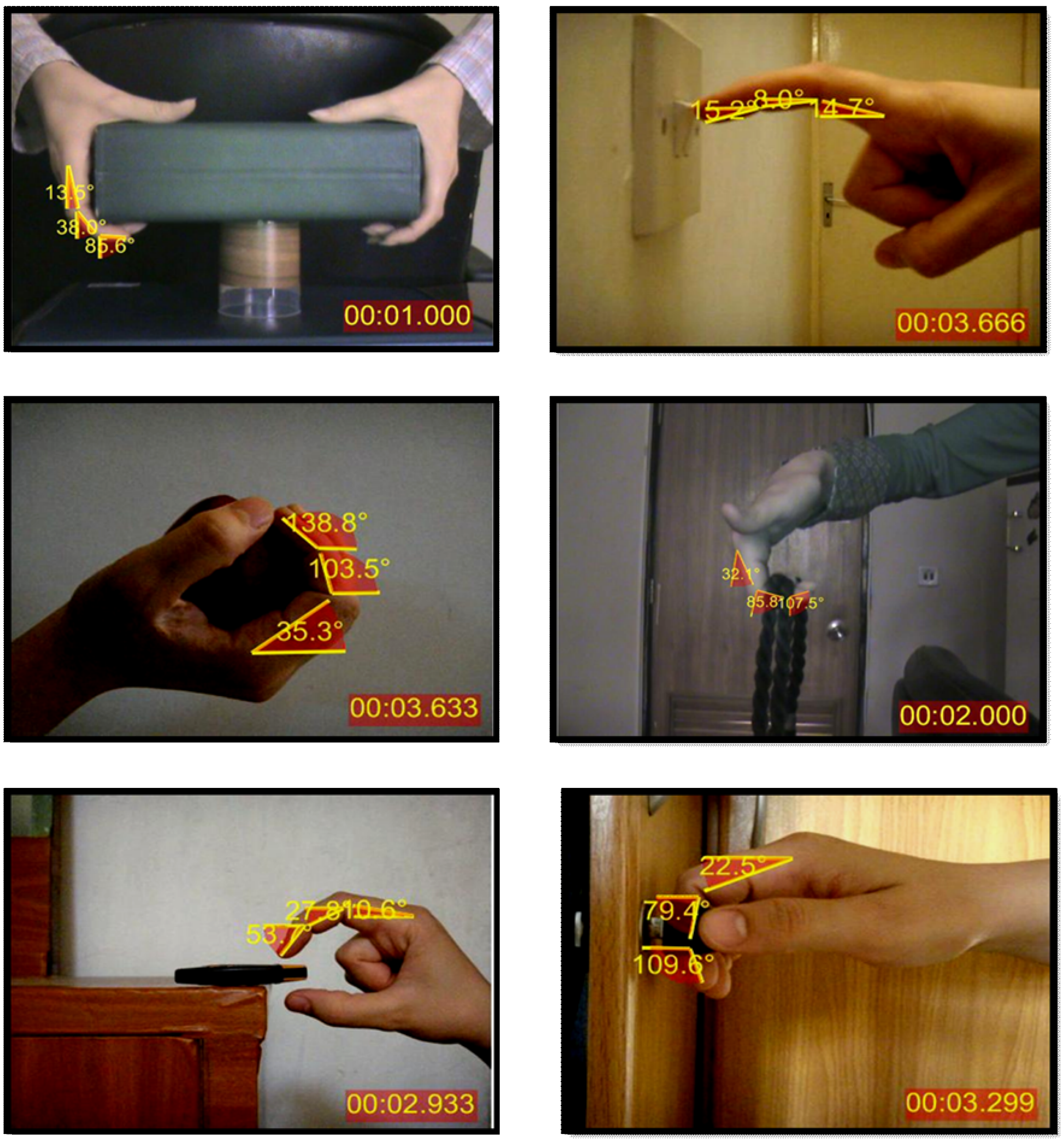


Fig.5. Snaps of Different Six Grips.

4.5.1. Cylindrical Grip

The cylindrical grip Fig.(6) was chosen because of its vitality to a wide range of people, especially for the working class in order to enhance their performance and facilitate their daily life. This grip recorded as frames (shots) by the digital camera, then several photos were chosen so as to measure the change in joints angles, the time period between successive chosen shots was different depending on the total time for each grip.

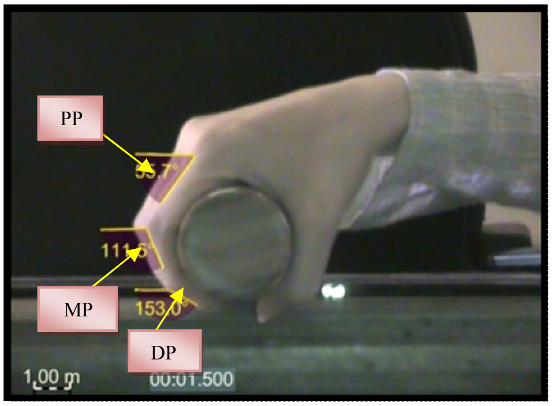


Fig.6. Mathematical Model of Cylindrical Grip.

1. Distal phalanx (DP)

The moments analysis of the distal phalanx for index finger shown in Fig.(7).

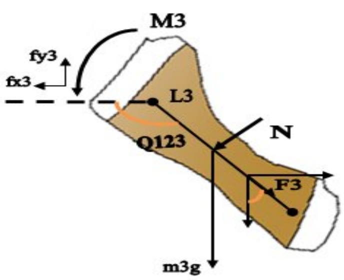


Fig.7. Free Body Diagram of Distal Phalanx of Cylindrical Grip.

$$\sum F_X = 0$$

$$N_3 \cos(\theta_{123} - 90) + F_{x3} - F_3 \cos\theta_{123} = 0 \quad \ldots(3)$$

$$\sum F_y = 0$$

$$m_3 g + N_3 \sin(\theta_{123} - 90) + F_3 \sin\theta_{123} - F_{y3} = 0 \quad \ldots(4)$$

$$\sum M = 0$$

$$m_3 g \frac{L_3}{2} \cos(180 - \theta_{123}) - N_3 \frac{L_3}{2} + M_3 = 0 \quad \ldots(5)$$

2. Middle Phalanx (MP)

The moments analysis of the middle phalanx for index finger shown in Fig.(8).

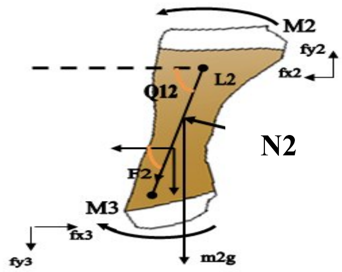


Fig.8. Free Body Diagram of Distal Phalanx of Cylindrical Grip.

$$\sum F_X = 0$$

$$N_2 \sin(\theta_{123} - 90) + F_{x3} - F_3 \cos\theta_{123} = 0 \quad \ldots(6)$$

$$\sum F_y = 0$$

$$F_2 \sin\theta_{12} + m_2 g - N_2 \cos\theta_{12} + F_{y3} - F_{y2} = 0 \quad \ldots(7)$$

$$\sum M = 0$$

$$m_2 g \frac{L_2}{2} \cos\theta_{12} - N_2 \frac{L_2}{2} - M_3 + M_2 + F_{y3} L_3 \cos\theta_{12} + F_{x3} L_2 \sin\theta_{12} = 0 \quad \ldots(8)$$

3. Proximal Phalanx (PP)

The moments analysis of the proximal phalanx for index finger shown in Fig.(9).

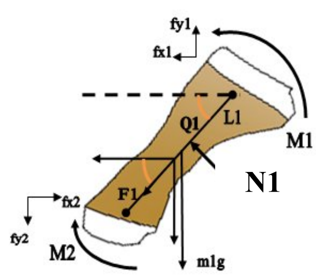


Fig.9. Free Body Diagram of Distal Phalanx of Cylindrical Grip.

$$\sum F_X = 0$$

$$N_1 \sin\theta_1 - F_{x2} + F_{x1} + F_1 \cos\theta_1 = 0 \quad \ldots(9)$$

$$\sum F_y = 0$$

$$F_1 \sin\theta_1 + m_1 g - N_1 \cos\theta_1 - F_{y1} + F_{y2} = 0 \quad \ldots(10)$$

$$\sum M = 0$$

$$m_1 g \frac{L_2}{2} \cos\theta_1 - N_1 \frac{L_2}{2} + M_1 - M_2 + n\theta_1 = 0 \quad \ldots(11)$$

4.6. Actuator Design (Muscle Wire)

In static analysis, the torque at joint *i* is given by the following equation:

$$T_i = F_{1i} d_i - F_{2i} d_i \quad \ldots(12)$$

In terms of the stress in the wires and assuming identical wires are uses

$$F_i = \sigma_i A_i \quad \ldots(13)$$

Equation (12) can be written as:

$$T_i = \sigma_{1i} A_i d_i - \sigma_{2i} A_i d_i \quad \ldots(14)$$

The wire cross-sectional area can, therefore, be expressed in terms of the wire stress values:

$$A_i = \frac{T_i}{d_{i(\sigma_1 - \sigma_2)}} \quad \ldots(15)$$

The chosen maximum low temperature strain for this work is 5%. From the above, the SMA wire lengths can be calculated: [2]

$$L = \frac{\Delta L}{z} \quad \ldots(16)$$

5. Results and Discussion

5.1. Result of Kinematics for Cylindrical Grip

The total time period of this grip was 1.5s with 14 shot. The angles of joints in each shot are illustrated in table (2), the maximum angle θ was 54.5º in metacarba phalengial joint at 1.4 s and the range of motion was (0º to 54.5º) for Metacarpaphalengeal joint, (0º to 106.7º) for Phalengealinterphalengeal joint and (0º to 153º) for distalinterphalengeal joint also the change of angle of all phalanx in this grip was the same for period (0-0.85sec) beyond this point the angle of metacarba phalengial joint would be constant at level 55º,while still increasing to specific point Fig.(10).

Table 2,
Kinematics of the Index Finger in Cylindrical Grip.

Angle of DIP joint (θ3) (degree)	Angle of PIP joint (θ2) (degree)	Angle of MCP joint (θ1) (degree)	Time (sec)
0	0	0	0
9.9	11.8	18.8	0.1000
15.1	19.0	22.3	0.3000
20.4	22.9	27.4	0.4000
25.2	25.0	30.4	0.5000
28.9	33.4	33.9	0.6000
34.6	34.2	38.0	0.7000
37.7	41.7	47.6	0.8000
56.8	56.5	51.7	0.9000
74.7	68.0	54.2	1.0000
89.3	78.1	54.2	1.1000
107.6	104.5	54.2	1.2000
130.1	106.2	54.2	1.3000
153.0	106.2	54.2	1.4000

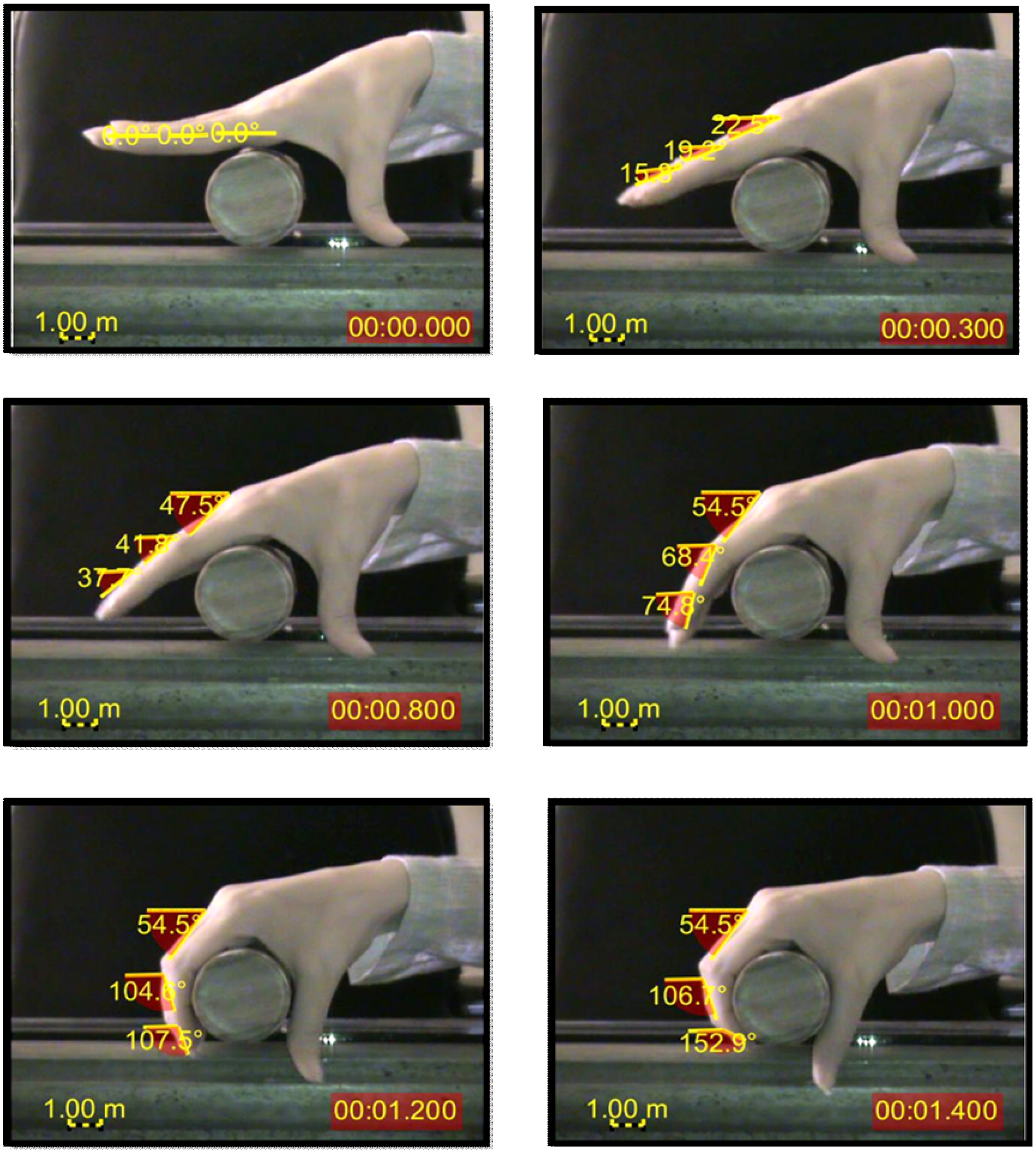
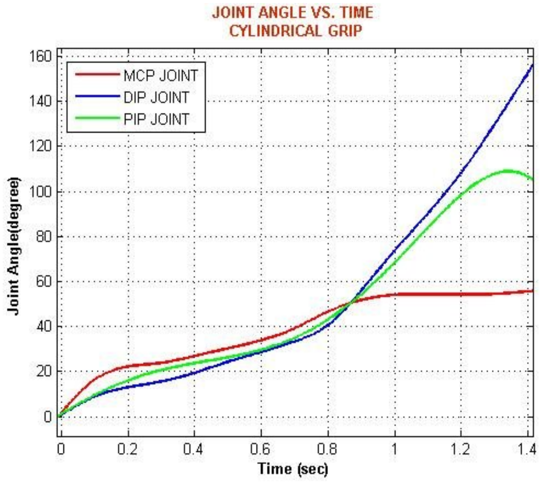


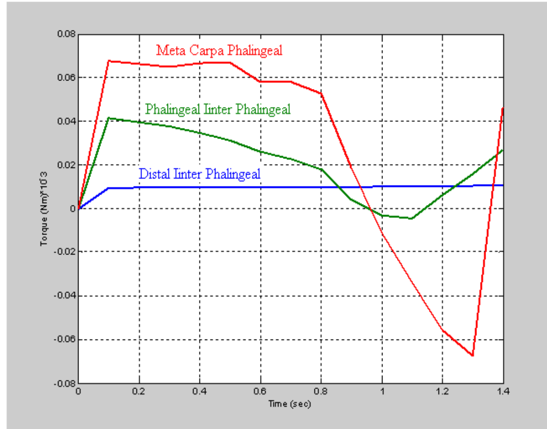
Fig.10. Snaps of Cylindrical Grip for Time from 0 to 1.4 s.

5.2. Results of Static Moment Analysis for Cylindrical Grip

In this grip an object with a cylindrical shape is assumed to be pulled. The object is supposed to affect on (Distalinterphalingial) and (Phalingealinterphalingial) joints, the reaction of this object assumed to be (unit force). From the Fig.(11) Can be noticed that Moment values are between (-0.00667 – 0.0668) Nm, and the maximum value was in the Metacarpaphalingial Joint at 0.5 s. Figures (11(a)) through (17(a)) illustrate the relationship between the joints angles and time while the Figs.(11(b)) through (17(b)) illustrate the relationship between Moment and Time for the distalinterphalengeal joint, phalengealinter phalengeal joint and metacarpaphalengeal joint for the seven grips.

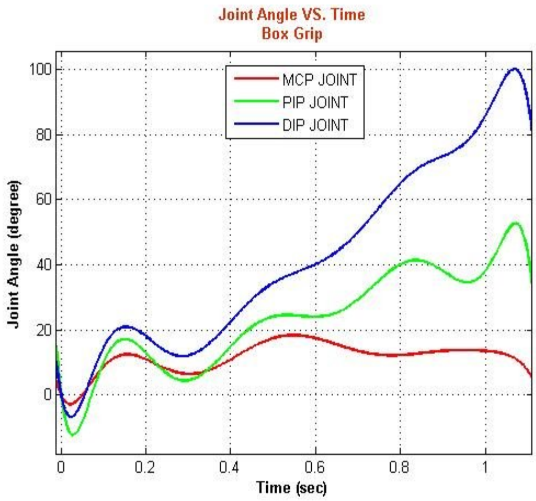


(a)

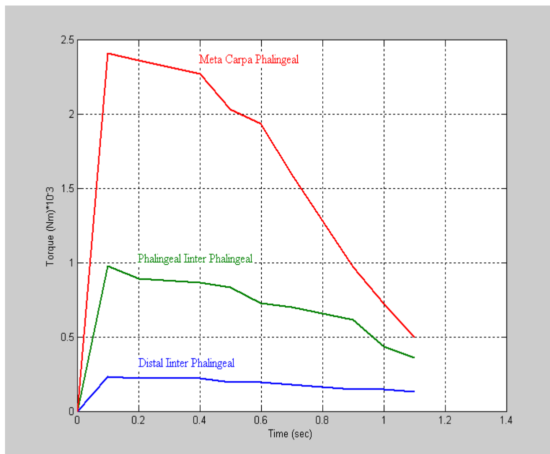


(b)

Fig.11. Cylindrical Grip.

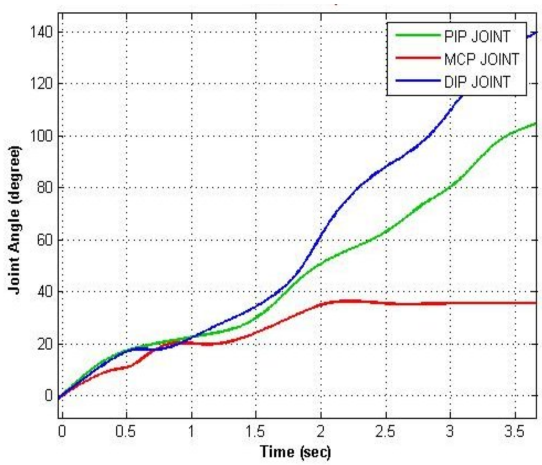


(a)

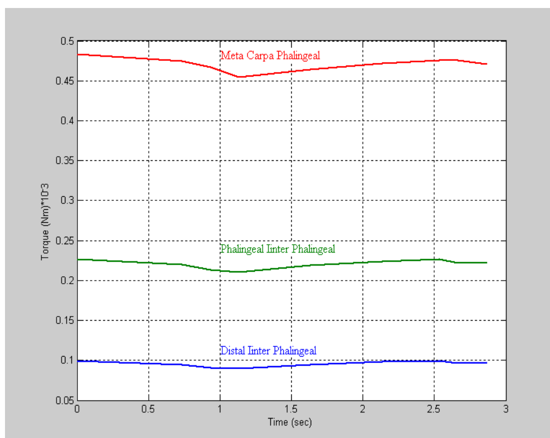


(b)

Fig.12. Box Grip.

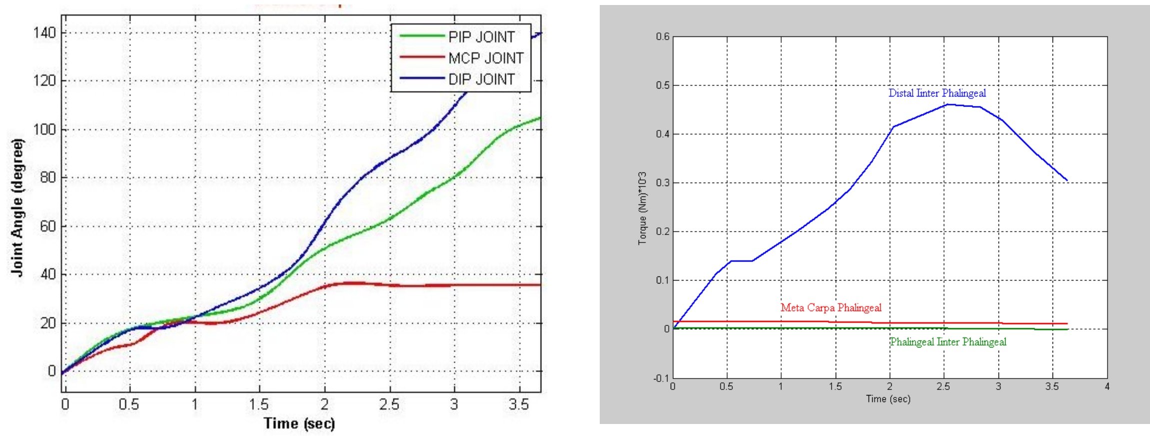


(a)



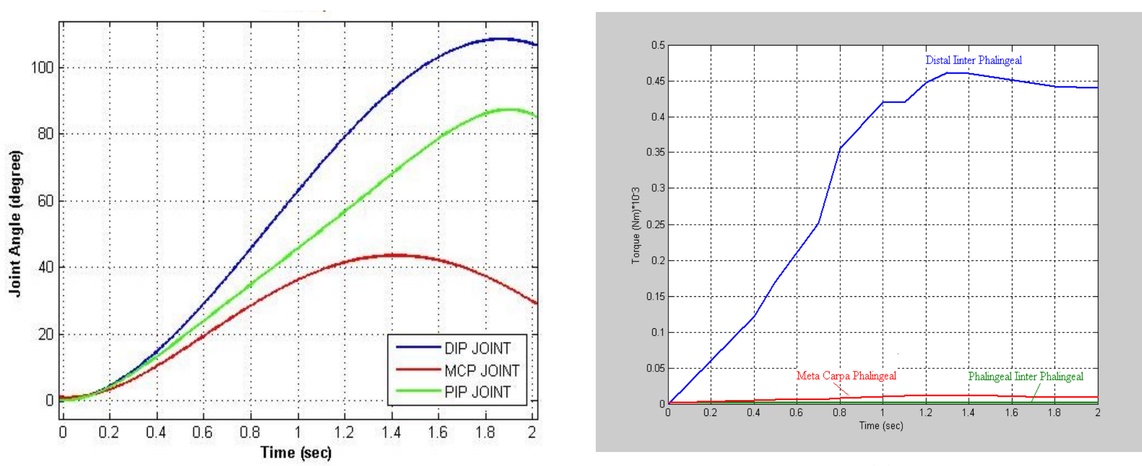
(b)

Fig.13. Push Grip.



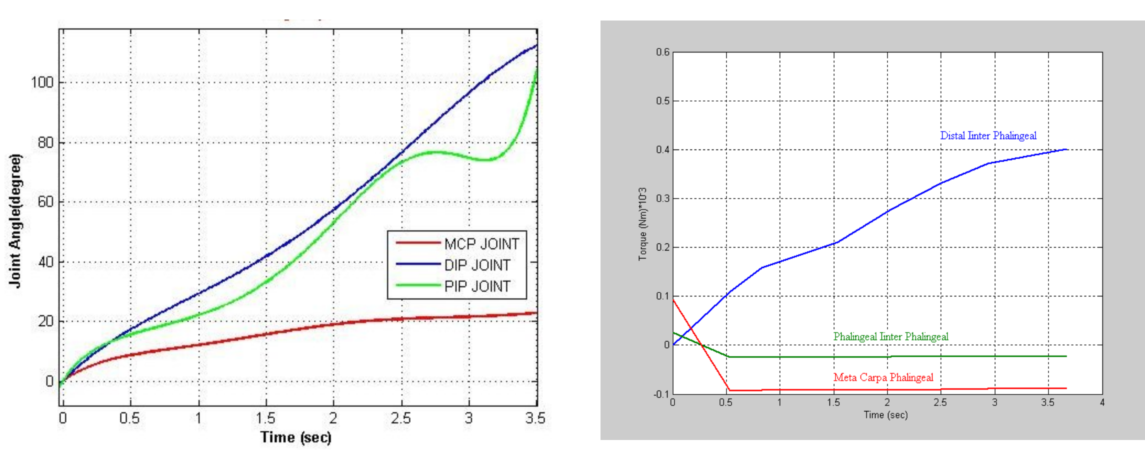
(a) **(b)**

Fig.14. Spherical Grip.



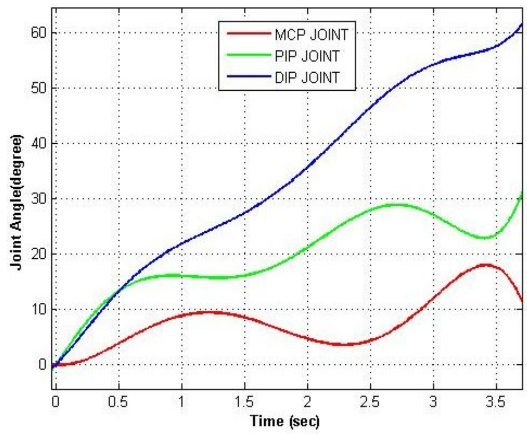
(a) **(b)**

Fig.15. Hook Grip.

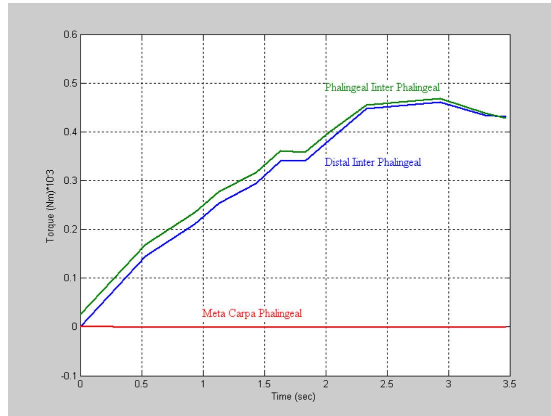


(a) **(b)**

Fig.16. Key Grip.



(a)



(b)

Fig.17. Tip Grip.

5.3. Results of Muscle Wire Design (SMA)

The muscle wire actuator design calculations require the maximum tensile stress at high temperature and the strain of the muscle wire at low temperature to be specified. To ensure that the maximum muscle wire fatigue life is obtained, a typical high temperature tensile stress of 170 MPa is used for Ni-Ti alloys. Furthermore, the recommended bias force that should be applied to extend a cooled muscle wire is 35 MPa [2].

Consider the maximum Moments that can occur at each joint then by applying the equations (12 to 16) founded the result that mentioned in table (3).

Table 3,
Length, Diameter, Actuation Forces for (SMA) Wire One and Two.

joint	Muscle wire Length (mm)	Muscle wire Diameter (µm)	Wire1 force (N)	Wire2 force (N)
MCP	86.95	752.2	300.0	62.19
PIP	144.6	486.9	126.6	26.04

Since high bandwidths are required, the actuation force can be distributed in to multiple muscle wire of smaller diameter and acting in parallel, therefore the Metacarpaphalengeal(MCP) wire1 force (300 N) would distributed in to tow hundred wire of (100 µm), Phalengealinterphalengeal (PIP) wire 1 force would be forty of (150µm), Metacarpa Phalengeal wire 2 force would be twenty of (150 µm) and Phalengealinterphalengeal wire 2 force would be eighteen of (100 µm).

6. Conclusion

1. The video recording method was viable method to obtain kinamatic analysis.
2. Dartfish's video management system helped to manage all the movement videos with ease and efficiency during hand moving since it consider each finger segment to be a rigid body, linked to each other by a joint. The software tools are used to get the stick figure representation that helped to find the kinematics.
3. The benefit of this study is to make design for artificial finger that mimics the natural human finger in different grips to be used in the field of rehabilitation and for robotic hand.
4. The muscle wire considered as the actuation system in the design because of its properties that was; low cost, small size, light weight, strong force, and high strength to weight ratio.
5. The human hand is an extraordinary example of how a complex system can be implemented, and how such a system is capable to perform very complex tasks using a combination of different elements.

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مفهوم التصميم الميكانيكي الإحيائي لليد البشرية الاصطناعية

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الخلاصة

هذه الدراسه تتركز حول تصميم ونمذجة الاصبع البشري (اصبع السبابة) في سبعة قبضات مختلفه (القبضة الاسطوانية ، قبضة رفع صندوق ، قبضة الضغط على زر ، قبضة الخطاف ، القبضة الكروية , القبضة الطرفية ,قبضة المفتاح).

تم في هذه الدراسه ابتداءا اجراء تصميم نموذج للمظاهر الكيناميتيكيه المثاليه الخاصه بحركة الاصبع البشري خلال هذه القبضات والتي تم ايجادها عن طريق تحليل التصوير الفيديوي الذي تم تسجيله باستخدام كاميرا تصوير فيديويه رقميه مثبته امام المستوى الجانبي اثناء حركة اليد البشريه, باستخدام برنامج التحليل الحركي (Dartfish) تم دراسة كينماتيكيه (حركية) لمفاصل الاصبع البشري خلال القبضات المختاره من التصوير الفيديوي .

في المرحلة التالية تم نمذجة هذه القبضات عن طريق عمل (تحليل العزوم الاستاتيكي) الذي يمكننا من حساب مقدار العزم المتولد في كل مفصل من مفاصل الاصبع بالاعتماد على النتائج المستحصلة من التحليل الكينماتيكي.

الخطوة الاخيرة في هذه الدراسة كانت عمل تصميم لوسيلة التحريك في هذا الاصبع الاصطناعي والتي تم اختيارها من نوع (الالياف العضلية الاصطناعية) بالاعتماد على النتائج التي تم استحصالها من (تحليل العزوم الاستاتيكي).