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A robust design of a prosthetic finger and its dynamic analysis

S. R. Kashef
Mechanical Engineering Department
Ferdowsi University of Mashhad
Mashhad,Iran.
Kasheftabrizian.seyedreza@mail.um.ac.ir

M. Davari
Mechanical Engineering Department
Ferdowsi University Of Mashhad
Mashhad,Iran.
davari.maryam@mail.um.ac.ir

A. Akbarzadeh
Center Of Excellence on Soft Computing and Intelligent Information processing,
Mechanical Engineering Department
Ferdowsi University Of Mashhad
Mashhad,Iran.
Ali_Akbarzadeh@um.ac.ir

***Abstract*— Dynamic responses of under-actuated prosthetic hands determine the performance and operation safety of these systems. In order to control the gripping force and to improve the grasping characteristics of the hand, it is necessary to analyze the dynamic responses of the system. This paper presents a forward dynamic model of a linkage being used in most of commercial prosthetic hands. The finger mechanism is composed of a four-bar linkage with one degree of freedom. Constrained Lagrange method is used to derive the dynamic equations of the finger. The three joint angles of the four-bar linkage are selected as the generalized coordinates of the system while the motor torque is chosen as the input. Since the mechanism has one degree of freedom, two kinematic constraints are also considered. The results of the dynamic equations of motion are compared to the responses of a software model of the finger, developed in a dynamic simulation software. The good agreement between the results verifies the dynamic model developed for the prosthetic finger.**

Index Terms - Prosthetic hand. Dynamic. Kinematics. Constrained Lagrange

I. INTRODUCTION

One of the fundamental human features that distinguishes us from other primates is the object manipulation by grasping capabilities of dexterous hand. According to our daily life, hand is one of the most important limb to do various activities. Loss of this extremity causes many problems in daily works; such people become unable to grasp or manipulate tasks. In the past years, hand amputees used a simple hook which had much less function in comparison to a real limb. Furthermore, it was very inappropriate in appearance; however, nowadays amputees can utilize a modern prosthetic hand that is so close to a real hand in terms of appearance and function. Worldwide, every year the number of amputees increases from150,000 to 200,000, which is added to the existing four million amputees. So the issue of prosthesis has been essential and worth exploring [1]. The mechanism of human hand is so complex that implementation its functions is a significant challenge. The most important requirement in prosthetic hand is to grasp objects of different sizes and shapes, in a stable and secure way. Other important parameters are lightweight and low-cost system, quick, easy and reliable control method that can be interpreted via a low-level control loop thus decreasing the cognitive load of the user and increasing patient acceptability. Hands such as bebionic3 andi-limb Ultra Revolution, can cost over US$ 35,000, which varies depending on the level of amputation [2]. Therefore, it is important to produce a bionic hand with low cost and easy operation to use for people with low purchasing power. Nowadays there are prostheses which give much better functionality, are acceptable to more amputees and are durable and convenient; nevertheless, these prostheses still have to overcome remarkable barriers in order to mimic a real hand [3]. From a mechanical perspective, it is a formidable challenge to integrate a large number of articulated DOF and corresponding actuators to manipulate a high dimensional structure. Moreover, increasing the actuated DOF of robotic hand results in decreased overall grip strength and also makes the system unstable [4]. Increasing the number of actuators means more probability of failure and need to repair, which requires a specialized tool and often segments that necessitate supplying or sent back to the manufacturer [5]. Subsequently, prosthetic hands must be easy to manufacture and easy to maintain.

Designers and manufacturers of artificial hands, have mainly used two different mechanisms: linkage-driven and tendon-driven. These mechanisms have some advantages and disadvantages. Many publishers have compared and mentioned the advantages of these mechanisms relative to each other. By using tendon-driven mechanisms, it is possible to place actuators outside the palm hand [6]; however, it is difficult to accurately recognize the relationship between actuator rotation and finger joint angles [7]. In viewpoint of Yoon et.al. tendon-driven mechanisms are structurally simpler than linkage ones.

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Meanwhile, linkage-driven mechanisms are preferred in applications where high output torques are required [8]. Birglen et.al. have mentioned that tendon-driven mechanisms have better performance than another model [9]; however, they agree with high forces that can be applied with linkage-driven fingers. Kabayashi et.al. have completely checked out the advantages and disadvantages of tendon-driven robotic hands. Based on their studies, in such kind, dynamic response is improved, joints stiffness is adjustable and fingers become lightweight. But, due to low rigidity of the joints, mechanical design and control strategy are complicated [10]. According to Xhi li et.al. researches, in a tendon-driven system it is easy to design an underactuated finger, nevertheless, they are considerably affected by friction. They have also discussed about the ability to apply greater forces and ease of hand control with linkage-driven ones [11]. In conclusion, it is observed that in a tendon-driven mechanism, light weight arm, underactuated fingers and more place in the palm can be achieved. Exerting more force to objects, robust links and simple control method due to specified kinematics and dynamics are the greatest features of a linkage-driven hand. In [12] a three phalanges linkage-driven finger has been introduced and claimed that it results to better grasping performance and more anthropomorphic motion rather than two phalanges ones. In [8] and [11] two self-adaptive finger mechanisms based on linkage have been recommended. Although Self-adaptive mechanisms can envelop more variety of objects, the probability of ejection and instability dramatically increases.

In this paper we present an artificial finger based on a robust linkage four-bar mechanism, widely used in commercial prosthetic hands such as bebionic hand [13]. Analyzing the finger mechanism movement and driving the dynamic equations of motion of the finger have been done. Lack of investigating of dynamic equations especially in linkage-driven mechanism is obvious.

II. MECHANICAL DESIGN

A. *Introduction*

The following figure shows human hand bone structure.

Fig. 1. Bone structure of human finger [14].

Each finger contains the metacarpophalengeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints which enable the finger movement. These joints work like hinges when the fingers are flexed or extended. The joints have articular cartilage which simplifies movement and acts as shock absorber. The first, second, third and fourth fingers all have three joints which imitate the MP, PIP, and DIP joints [15]. In Table I geometrical dimension of a typical human index finger [16] in comparison with the designed finger is shown. The resemblance between total length of both models is obvious.

B. *Objective*

The human hand functions imitation capacity is the ultimate goal that only some of them are obtainable yet; for instance, most of the prosthetic hands have fewer freedom in comparison with human hand which has led to perform only some of human hand grasp postures. It is worth noting that having all three phalanges on each finger helps to conform better to the shape of the object, but increases the finger weight and also reduces the mechanism robustness [17]. All the efforts have done to closely reach the human finger function while having a simple and easy manufacturable structure. Eventually, by assessing different mechanisms, in order to reach a mechanism which is likely for commercializing and manufacturing, we (Robotic Group at FUM) have chosen a two phalanges linkage-driven finger mechanism due to its simplicity, robustness, light weight and stability.

C. *Mechanical Design*

Fig. 2 shows the model of the designed finger. There are three links which two of them are as proximal and distal phalanges and another one as coupling. Coupler link makes the relationship between proximal and distal phalanges.

We have also considered a slut in the first phalange structure and a spring in the joint between proximal and distal phalanges. When an external shock applied on the finger it will slide inside the slut, therefore the slut plays roll of a shock absorber as like as a real hand. After the shock, the spring returns the finger.

TABLE I.
PHALANGES LENGTH OF A TYPICAL HUMAN INDEX FINGER [16] AND THE DESIGNED FINGER

	anthropomorphic data			
	Index		**Designed finger**	
	Dimenshion (mm)	Angle (deg)	Dimenshion (mm)	Angle (deg)
Proximal	43	78	46	90
Middle	25	105	-	-
Distal	23	83	42.5	102

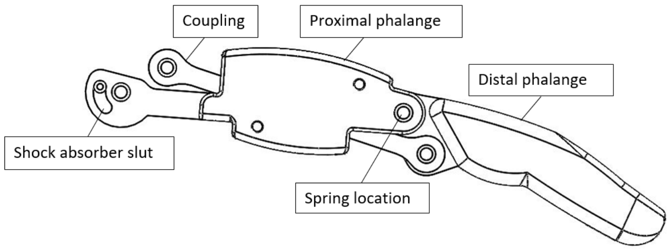

Fig. 2. Solid model

III. Finger Analysis

A. Kinematics

In order to define kinematic relations among links of the mechanism Fig.3 is used. There are four vectors which are related to four-bar linkage and four angles respectively. Vector number 1 is proximal link, number 2 is coupling, number 3 is one edge of the distal ternary link and number 4 is ground link. All the angles are defined clockwise. Geometrical dimensions and mass properties are shown in Table II. The lengths that are shown, have been determined by optimization of the link's lengths in order to mimic human natural motion and having dimensions close to a typical human finger. Mass properties are calculated from considering aluminum density for mechanical components. We have employed aluminum because of its low density and high strength.

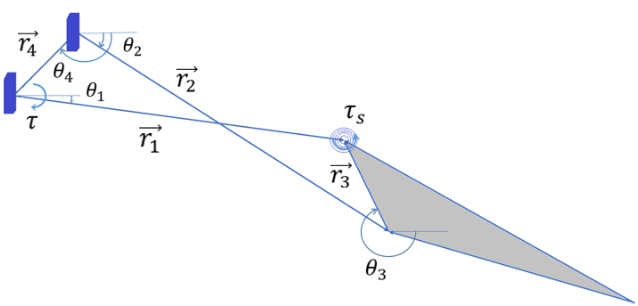

Fig. 3. Model diagram

TABLE II.
MODEL PARAMETERS

Row	Important parameter		
	Title	*Unit*	*Dimension*
1	r_1	mm	46
2	r_2	mm	44.4
3	r_3	mm	7.7
4	r_4	mm	8.5
4	m_1	gr	16.91
5	m_2	gr	2*0.86
6	m_3	gr	14.16

The kinematic relation is written as follows:

$$\vec{r}_1 + \vec{r}_4 = \vec{r}_2 + \vec{r}_3 \quad (1)$$

Which can be divided into two horizontal and vertical directions:

$$r_1 \cos(\theta_1) + r_4 \cos(\pi - 0.49) - r_2 \cos(\theta_2) - r_3 \cos(\theta_3) = 0 \quad (2)$$

$$r_1 \sin(\theta_1) + r_4 \sin(\pi - 0.49) - r_2 \sin(\theta_2) - r_3 \sin(\theta_3) = 0 \quad (3)$$

The system of the above two coupled equations can be solved for various θ_1 and hence the fingertip trajectory and finger workspaces can be achieved.

B. Fingertip Trajectory

Kinematic parameters of the system specify the trajectory of the finger. The fingertip trajectory has a direct effect on the hand workspace which envelops the different types of grasp posture and imitation natural movement of human fingers. The simulated fingertip trajectory is shown in Fig. 4.

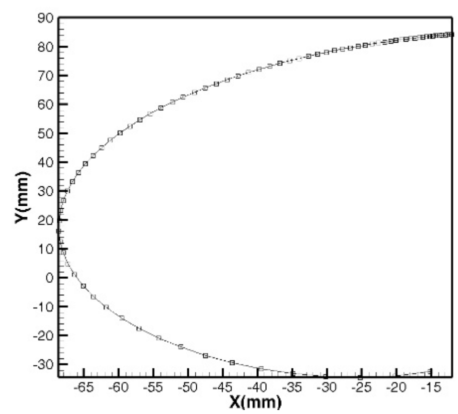

Fig. 4. The fingertip trajectory of the designed finger

Fig.5 and Fig.6 show different postures of the designed finger and human index fingertip trajectory, extracted from Kamata et.al. researches [18], respectively.

Fig. 5. Different postures of the finger

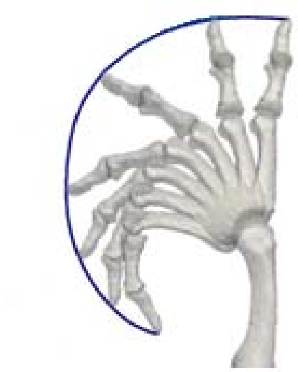

Fig. 6. The fingertip trajectory of human index finger [18].

C. Dynamics

There are two common approaches to drive dynamic equations of a system: newton method and energy method. In newton's method the number of equations are more than the energy methods because the internal forces or the forces which do not do any work must be calculated. Besides, energy methods are more general and they can be used in almost all systems. So we have employed Lagrange method to drive the equations. Note that the Lagrange method is a derivation of Hamilton method when there are just conservative forces.

In the mentioned finger mechanism there are three moving links which are related to each other through the four-bar mechanism. Because of the complicated kinematic relation among angle of the links, it is extremely hard to write the angle of link 2 and 3 based on the driver link. So we have used the Lagrange constrained method. The Lagrange constrained formula is as follows:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_m}\right) - \frac{\partial T}{\partial q_m} = \lambda_r a_{rm} + Q_m \tag{4}$$

Where:

$T = T_1 + T_2 + T_3 =$ Kinetic energy of the system
$q_m (m = 1,2,3) =$ Lagrangian coordinate
$\lambda_r (r = 1,2) =$ Lagrange multiplier
$Q_m =$ Generalized force associated with q_m
$m = (1,2,3) \rightarrow Q_m = (\tau - \tau_s, 0, -\tau_s)$
$\tau =$ Driving torque
$\tau_s =$ Spring torque

We have employed 3 generalized coordinates (θ_1, θ_2, θ_3) and as the mechanism has one degree of freedom, two kinematic equations have to be considered.

$$a_{rm} = \frac{\partial \emptyset_r}{\partial q_m} \tag{5}$$

Where $\emptyset_r (r = 1,2)$ are kinematic equations or constrained equations as mentioned in (2) and (3).

Via 3 equations which are derived from (4) and two kinematic equations and also by using Euler integration formula as follows, the dynamic equations can numerically be solved.

$$\theta(t + \Delta t) = \theta(t) + \dot{\theta}(t)\Delta t + \frac{1}{2}\ddot{\theta}(t)\Delta t^2 \tag{6}$$

$$\dot{\theta}(t + \Delta t) = \dot{\theta}(t) + \ddot{\theta}(t)\Delta t \tag{7}$$

The driving torque is applied to link1 based on the downward function:

$$\tau = 10t + 1 \quad \text{(N.mm)} \tag{8}$$

The spring stiffness is 1(N.mm/rad).

The following figures show the result of the numerical method of angles variations in comparison with the output of the software model of the finger developed in Adams, shown in Fig.10. The agreement between results is good.

The finger flexion range is relevant to the ordinary workspace of the finger in daily tasks, occurred in 0.3 seconds.

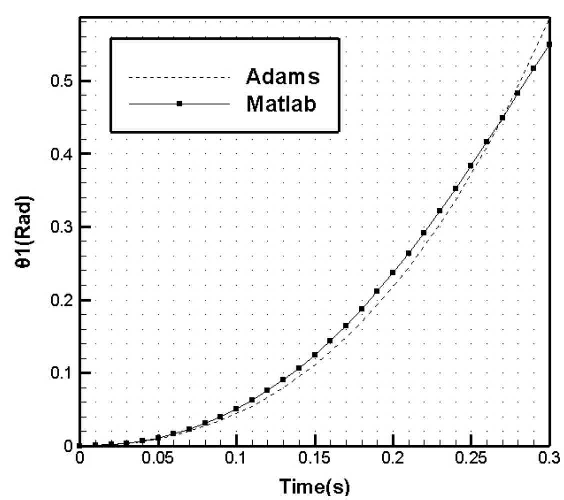

Fig. 7. Comparison of angular displacement of link 1

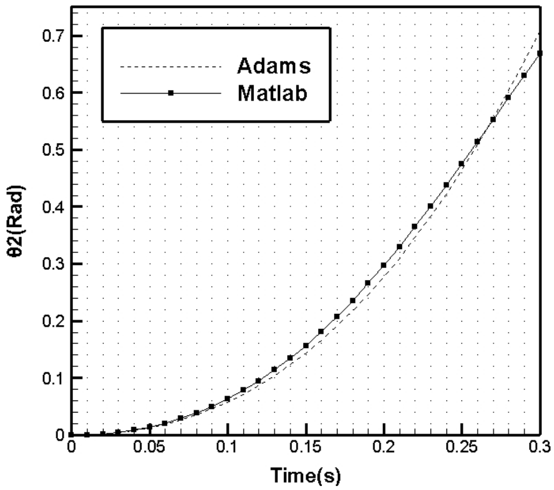

Fig. 8. Comparison of angular displacement of link 2

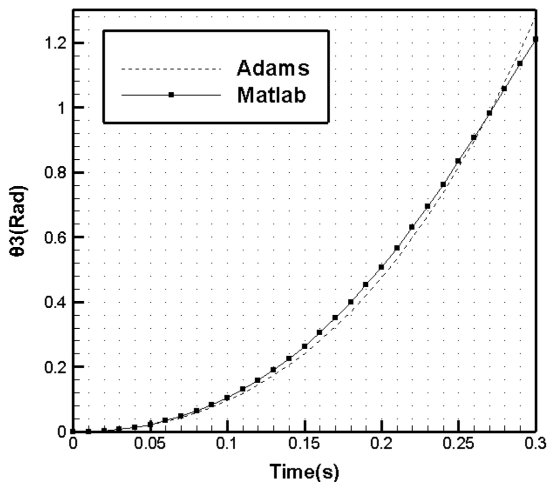

Fig. 9. Comparison of angular displacement of link 3

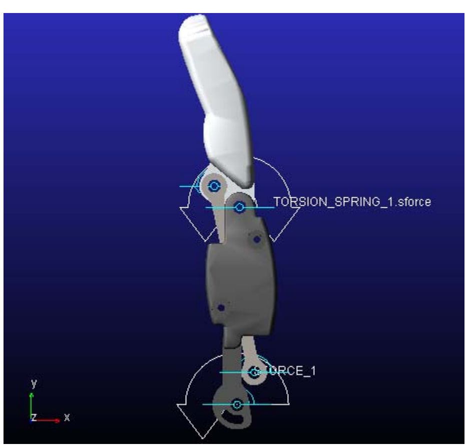

Fig. 10. Software model of the finger developed in Adams

IV. CONCLUSION

In this paper, the finger mechanism of a prosthesis hand is considered and the dynamic model of the system is developed. The finger mechanism includes a four-bar-linkage with one DOF. Using the kinematic analysis of the finger, the fingertip trajectory is extracted. It is shown that the trajectory of the proposed finger closely mimics the motion of a human finger. Even though a phalange has eliminated in the proposed finger, the main functionality of the finger is preserved. In order to analyze the dynamic responses of the finger, the constrained Lagrange method is used to derive the dynamic equations of the system. Two extra generalized coordinates are considered to facilitate the derivation of the dynamic model, leading to imposition of two kinematic constraints. Finally, the developed dynamic model of the finger is verified through comparing the results of the dynamic equations with the results obtained from a dynamic simulation software.

In future work, we can use the dynamic analysis to control the parameters of motion with or without external forces and improve the grasping response characteristics.

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