Design and Analysis of an Underactuated Anthropomorphic Finger for Upper Limb Prosthetics

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Abstract— **This paper presents the design of a linkage based finger mechanism ensuring extended range of anthropomorphic gripping motions. The finger design is done using a path-point generation method based on geometrical dimensions and motion of a typical index human finger. Following the design description, and its kinematics analysis, the experimental evaluation of the finger gripping performance is presented using the finger 3D printed prototype. The finger underactuation is achieved by utilizing mechanical linkage system, consisting of two crossed four-bar linkage mechanisms. It is shown that the proposed finger design can be used to design a five-fingered anthropomorphic hand and has the potential for upper limb prostheses development.**

I. INTRODUCTION

Over the last few decades, there were a great number of studies on developing and experimental trials of novel upper limb prosthesis designs. Aiming to provide more dexterous and advanced grasping capabilities, modern upper limb prostheses utilize advances of robotic hand research [1]. Pioneer research on the development of multi-fingered humanoid robotic hands started in early 1980s [2], [3]. The hand design utilized tendon-driving mechanisms to actuate fingers. Usage of tendons provides the design advantage to place actuating elements outside the hand palm and use relatively large high torque actuators [4]. However, the relationships between finger joint angles and actuator rotation is relatively complex in tendon-driven mechanisms, requiring explicit coupled kinematics for accurate and dexterous control [5]. Additionally, tendon-driven systems may not be reliable for long-term usage and control [6]. With respect to the upper limb prostheses, the presence of bulky actuators outside the hand of the protheses requires additional space for actuating system in the prothesis arm [7].

In contrast, there have been proposed various designs of underactuated artificial fingers based on mechanical linkage mechanisms. The LISA hand [8] uses five motors to actuate five fingers and has 14 joint degrees of freedom (DOF). Each of the LISA fingers is composed of multiple-class block-linkage-slot transmission mechanisms, multiple springs and only one motor with a reducer. Self-adaptation for good grasping performance is designed as the main function of the LISA finger. Another design, the NAIST hand, has a total 12 DOF in four fingers. Each finger is designed to provide three DOF: two DOF for the metacarpal phalangeal (MP) joint and one DOF for the proximal interphalangeal (PIP) joint; the distal interphalangeal (DIP) joint is coupled with the PIP joint [9]. A novel three-axis gear driving mechanism has been developed without the use of tendons. It enables placement of all three electrical motors actuating the finger joints in the palm region. There are other compact robotic hand designs have been proposed utilizing hand embedded electric motors and gear systems for finger actuation without use of tendons [10]–[14]. As linkage mechanisms consist of rigid links and transmission gears, the finger and hand kinematics can be modeled and solved as a standard kinematics problem for control purposes.

Ideally several design requirements can be emphasised for designing robotic hands suitable for upper limb prosthetics: the hand and fingers should have good humanoid appearance and sizes, they are able to preform common grasp patterns of objects of a size of the order of the hand [1]. On the other side, the hand and fingers should have simple structure, be easily controlled and have low manufacturing costs. Most of present dexterous robotic hands and fingers could not balance the above aspects. Commercially available traditional dexterous robotic hands are very complex in architecture and very expensive in cost [8]. As human hands are characterized by their flexibility and dexterity to perform different tasks, requiring high stability and accuracy, there is a clear need for additional research in this direction.

This paper presents the design and analysis of an underactuated finger mechanism with three phalanges for upper limb prosthesis design. Presently, a lot of recently proposed tendon-driven prothesis prototypes and commercially available upper limb prostheses utilize the two-phalanx finger system [1], [15], [16]. Finger distal phalanges in such finger mechanisms are rigidly combined with the intermediate phalanges under certain angle ensuring basic grasping capabilities of a prothetic hand. On the contrary, the proposed finger design consists of three phalanges combined using four-bar linkage mechanisms to couple the finger DIP, PIP and MP joints. This results to larger workspace, enhanced gripping performance of the finger compared with the traditional two-phalanx finger designs, more natural grasp and finger movement as experientially demonstrated with the designed finger prototype.

The organization of the paper is as follows. Section II outlines the design of the underactuated finger mechanism whereas the finger kinematics analysis and experimental studies of the finger gripping performance are presented

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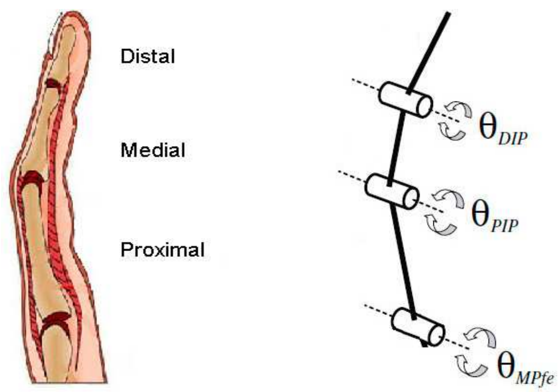
in Section III. Some conclusive remarks and future work directions are shown in the conclusion section.

II. UNDERACTUATED FINGER DESIGN

The finger design is based on the three main design requirements, which are an anthropomorphic motion, appropriate geometrical dimensions and a simple low-cost mechanical system of the finger. Initially, the human finger anatomy has been taken as a reference for the draft design. It was decided to design a finger mechanism with three joints and three phalanges due to stable and dexterous grasping, excluding abduction/adduction at an MP joint. The human finger and proposed finger schematics are shown in Fig. 1.



(a) (b)

Fig. 1. (a) The human finger anatomy and (b) mechanism schematics of the proposed finger.

The analysis of the previous research in this direction revealed an underactuated finger design with a linkage-based mechanism presented in [17]. The finger has one DOF mechanism that reproduces human-like grasping and a compact linkage system consisting of two crossed four-bar linkage mechanisms. However, the finger presented in [17] is not directly suitable for use in upper limb prostheses due to its non-anthropomorphic appearance and limited range of motion. The proposed in this paper finger design is characterized by an extended range of anthropomorphic gripping motions, anthropomorphic appearance, compact size and different actuation system.

To design a finger mechanism suitable for upper limb prosthesis the authors have adopted a path-point generation method to sketch the finger mechanisms and links matching the dimensions of a human finger presented in [18] and in Table I. As a result, an initial finger outline with a linkage system replicating a human finger motion has been developed using the SolidWorks 3D mechanical design software as illustrated in Fig. 2. However, the analysis of the initial finger sketch revealed the link interference with interphalangeal joints. Therefore, the linkage design was iterated to optimize the links geometry using the SolidWorks' Sketch Blocks tool, a special tool for designing planar mechanisms. Initially, the finger working zone was restricted by the link geometry. After iterative design optimization, the complete finger assembly consisting of the links and phalanges was developed

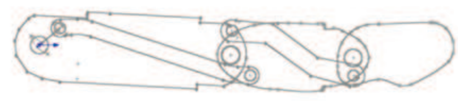


Fig. 2. The initial sketch of the finger mechanism with a linkage system.

as shown in Fig. 3. The comparison of the geometrical dimensions and limiting angles of rotation of the proposed finger mechanism with a typical index human finger [18] given in Table I shows close resemblance.

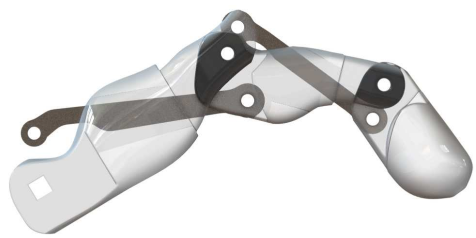


Fig. 3. 3D rendered model of the final finger mechanism.

Taking into account the design requirements,

TABLE I

GEOMETRICAL DIMENSIONS OF A TYPICAL HUMAN INDEX FINGER [18] AND THE PROPOSED FINGER MECHANISM.

	Human finger		Finger mechanism	
	Dimension	Angle	Dimension	Angle
Distal Phalanx	23	78	24	90
Medial Phalanx	25	105	29	100
Proximal Phalanx	43	83	42	85

III. FINGER ANALYSIS AND PERFORMANCE

A. Kinematics Analysis

The mathematical model for the finger motion trajectory analysis is derived using vector-loop-closure equations for the coupled system of two four-bar linkages of the finger mechanism shown in Fig. 4(a). The vector diagram of the finger kinematics is presented in Fig. 4(b) with the angles defined positive between the right horizontal line to the link vectors in the anti-clockwise direction.

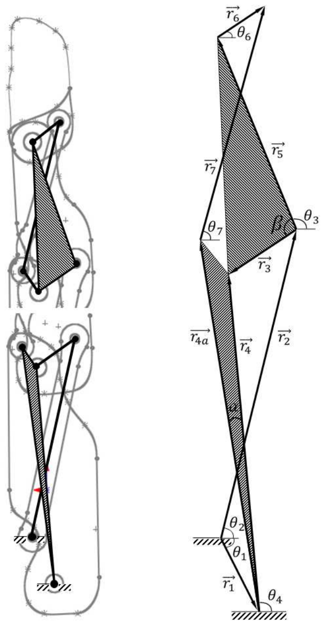
Using the notations from Fig. 4(b) the finger vector-loop closer equations can be written as follows [19]:

$$\vec{r}_1 + \vec{r}_4 = \vec{r}_2 + \vec{r}_3; \tag{1}$$

$$\vec{r}_1 + \vec{r}_{4a} + \vec{r}_7 = \vec{r}_2 + \vec{r}_5 + \vec{r}_6. \tag{2}$$

By writing the XY components for each vector-loop-closure equation and separating the two vector equations into four XY scalar component equations:

$$\begin{aligned} r_1 cos\theta_1 + r_4 cos\theta_4 = r_2 cos\theta_2 + r_3 cos\theta_3; \\ r_1 sin\theta_1 + r_4 sin\theta_4 = r_2 sin\theta_2 + r_3 sin\theta_3 \end{aligned} \tag{3}$$



(a) (b)

Fig. 4. A system of coupled four-bar linkages of the finger mechanism (a) and its vector representation (b).

$$
\begin{aligned}
r_1 cos\theta_1 + r_{4a} cos\theta_{4a} + r_7 cos\theta_7 = \\
r_2 cos\theta_2 + r_5 cos\theta_5 + r_6 cos\theta_6; \\
r_1 sin\theta_1 + r_{4a} sin\theta_{4a} + r_7 sin\theta_7 = \\
r_2 sin\theta_2 + r_5 sin\theta_5 + r_6 sin\theta_6,
\end{aligned}
\tag{4}
$$

where $\theta_5 = \theta_3 - \beta$ and $\theta_{4a} = \theta_4 + \alpha$, α and β are constants.

The system of four nonlinear equations (3) - (4) with four unknown angles $\theta_3, \theta_4, \theta_6, \theta_7$ can be solved in two stages, one for each mechanism loop, using MATLAB for the finger position analysis. Figure 5 illustrates the simulated fingertip trajectory and the finger workspaces for different finger postures starting from the straight finger until the closed grip position. Comparative analysis of the simulated fingertip path and the finger workspace with a typical human finger [20] on the same scale showed close convergence.

B. Gripping Performance

One of the most important hand design requirements is the capability to grasp objects with different sizes and shapes. The prototype of the designed underactuated finger was manufactured to experimentally verify the simulated grasping motions by mimicking natural movement of a human index finger as shown in Fig. 6. As clear from the figure the proposed finger mechanism is capable to grasp cylindrical objects with different diameters. Moreover, the three-phalanx finger design allows to perform a hook grasp of a small diameter white board marker that would not be possible to execute with traditional two phalanx fingers used in present upper limb protheses. The figure also demonstrates the finger anthropomorphic motion executing a usual human daily activity such as clicking of a PC mouse button.

The gripping force of any end-effector depends on its actuating mechanism. In the current design, a worm gear drive mechanism is utilized to transfer the motion from the Faulhaber 1226 actuator to a spur gear. The spur gear is rigidly connected to a proximal phalanx at the MP joint of the finger and actuates the finger. This actuation system demonstrates non-backdrivability property; consequently, the finger can actually resist much larger forces than it can exert [21]. Conducted experimental tests with the finger prototype showed that the actuation power was sufficient for executing primitive grasps. The maximum fingertip force was observed to be 2 N.

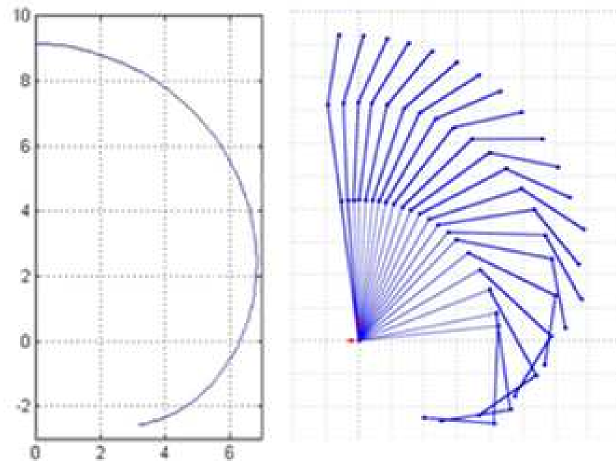


Fig. 5. The fingertip trajectory and finger workspace

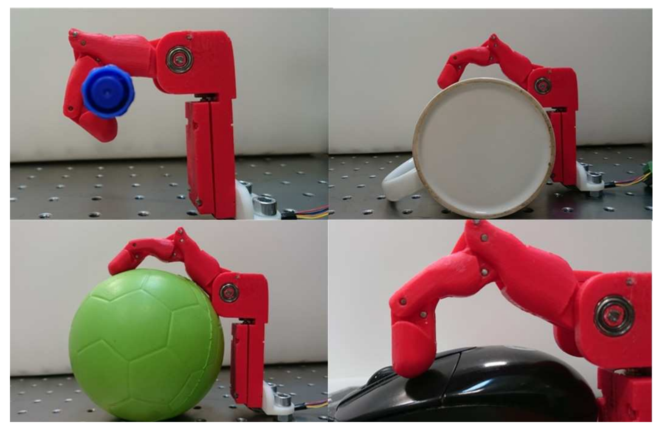


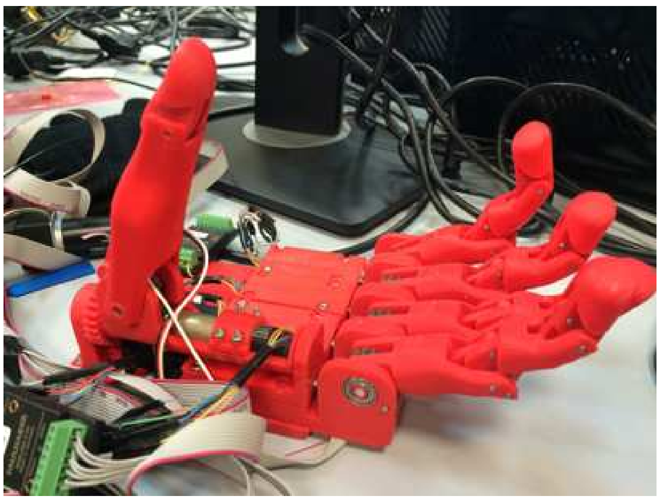
Fig. 6. Gripping performance of the finger prototype.

IV. CONCLUSIONS AND FUTURE WORK

This paper presents the design of an underactuated anthropomorphic finger design. The human-like finger motion was achieved by testing different linkage configurations. The kinematics analysis was used to simulate the fingertip trajectory and finger workspace. It was shown that the proposed finger design closely mimics natural human finger motions.

The proposed finger design has three advantages: a) anthropomorphic appearance, compact size and embedded linkage system b) actuation of three phalanges of the finger mechanism through a simple linkage system; c) the finger

(a)



(b)

Fig. 7. (a) Rendered 3D model of the five-fingered hand desing and (b) its 3D printed prototype.

prototype can be manufactured using a low-cost 3D printer due to simplicity of the manufactured parts.

Future work involves building a fully functional bionic hand prototype. Currently, the first iteration of a five-fingered hand 3D printed prototype is in process of assembly and testing as illustrated in Fig. 7. The thumb finger of the hand is being designed to ensure basic human hand grasps. It is also planned to develop a myoelectric control of the prosthetic hand prototype and eventually design an upper limb prosthesis.

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