An under-actuated mechanism for a robotic finger

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Abstract — Robotic hands can be applied in different applications such as prosthesis, humanoid robots, industrial robotic manipulators and other kinds of robotic arms. Introduction of robotic technology into the field of prosthesis has resulted a higher quality of life for amputees. In this paper an under-actuated mechanism which has the self-adaptation ability is proposed to be used in the fingers of the hand prosthesis. The mechanism is a modification of the cross bar mechanism and it shows grasping adaptation ability for different geometries. In addition the mechanism is capable to generate dexterous grasping patterns making a paradigm shift from the conventional linkage mechanisms used for fingers which only has the capability for the grasping. Kinematic analysis, mathematical simulation and computer simulations were carried out to evaluate the effectiveness of the mechanism. Furthermore a new parameter, degree of adaptation is introduced to evaluate the performance of the under-actuated finger mechanisms.

Keywords — finger mechanism, hand prosthesis, under-actuation, linkage mechanism, grasping adaptation.

I. INTRODUCTION

Robotic hands have been developed all over the world by different researchers with the intention of using them in robotic grippers, humanoid robots and robotic prosthesis. UTAH hand of MIT [1], Stanford hand of JPL [2], Belgrade hand of USC [3], DLR hands [4], iLimb hand of touch bionics [5], bebionic hand [6] and Vincent hand [7] are some of the pioneering robotic hands currently available. Amongst, iLimb, bebionic, hand and Vincent hand are the leading counterparts in the area of robotic prosthesis. Prosthesis restores the lost limb functions and the appearance of the lost limb, thus enabling the amputee to perform Activities of Daily Living (ADL). Finger or hand impairment is a widely occurring limb amputation due to industrial accidents, road accident and war casualties. Together with fingers the hand can be considered as the end-effector of the upper extremity and it directly interacts with the surroundings during ADL. Therefore, replacement of the amputated hand or fingers is very important to maintain the amputees’ physical and psychological interaction with the environment.

In order to handle objects with different geometries, hand is arranged in different grasping modes during ADL [1]. Metacarpophalangeal (MP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints are arranged in different configurations in order to make different grasping modes, especially changing the joint angle for flexion/extension of the finger. Therefore, a hand prosthesis should also have the capability of generating the required grasping modes to assist the ADL. A finger mechanism should have 3DoF in order to generate varying joint angles as the human finger. Even though several researchers [2], [3] have attempted to accommodate the requirement in their designs only few of them are capable of providing human alike motion for the finger mechanism. Under-actuation principle is one of the commonly employed strategies for finger designs. A mechanism is said to be an under-actuated when it has fewer actuators than the available degrees of freedom [8]. Several researchers [9]–[16] have proposed under-actuated finger mechanisms and hand designs. Among these, most of the fingers are capable of generating human alike cylindrical grasping mode to grasp cylindrical objects. Further, these designs are capable to adopt according to the geometry of the cylindrical object that is being grasped, due to the spring-link construction of the mechanism. During the grasping, they follow the basic sequence of operations shown in Fig. 1[15], [17]. With this sequence of operation it is not possible to generate the grasping patterns such as palmar, tip or hook those involve fingertip. This paper proposes an under-actuated mechanism that can be used as a finger mechanism of anthropomorphic hand prosthesis. The proposed mechanism can be employed to generate the grasping modes: palmar, tip and hook. In addition to the mechanism, a parameter called degree of adaptation is intro-
The paper is arranged as follows. Next section presents the design approaches of finger mechanisms. Section 3 presents the mechanical design of the proposed under-actuated finger mechanism. It will be followed by the kinematic and velocity analysis of the proposed finger mechanism in section 4. Discussion and conclusion are presented at the final section.

II. DESIGN APPROACHES OF FINGER MECHANISM

In this section, biomechanics towards the development of finger prosthesis is discussed prior to present the various design approaches used in the literature.

Hand is a combination of 27 bones attached together with 29 joints. It consists of more than 30 muscles and tendons to actuate the joints for the motions. 05 digits in the hand make 03 different types of joints: carpometacarpal (CMC), metacarpophalangeal (MP) and interphalangeal (IP). The first digit, thumb has a freely movable saddle joint as its CMC joint, further its MP joint is a bicondylar joint. Second and the third digits, respectively index and the long finger comprises of fixed CMC joints whereas forth and the fifth digits, respectively ring and the little finger comprises of flexible CMC joints. Except the thumb, other 4 digits have a condylar joint as their MP joints. MP joint of the thumb contributes to the flexion/extension. MP joints of the other four fingers contribute to flexion/extension and abduction/adduction of the fingers. In addition, thumb has a single IP joints while all other fingers have 2 IP joints namely Proximal IP (PIP) and Distal IP (DIP) joints. Both PIP and DIP joints are bicondylar and they contribute only to finger flexion/extension.

The movements of the finger depend on the complex synergist and antagonist relationship between the extrinsic flexors, extensors and intrinsic muscles. Extrinsic muscles show a multi-articulate behavior and capable of generating motion at multiple joints. Table 1 shows the muscles that contribute to the motions of the each finger. Fig. 2 shows the anatomy of the index finger. Further Kim et al. [19] proposed a mathematical model for the human finger. Accordingly, the DIP and PIP joints are mathematically modeled as revolute joints which support the finger flexion/extension. MP joint of the finger is mathematically modeled as a saddle joint which supports the flexion/extension and the abduction/adduction in two different perpendicular axes.

Obtaining 3 DoF in a finger design is a cumbersome task while maintain the anthropometry, in a space constrained surrounding for a hand design. However several researchers have followed different approaches in their finger designs to obtain the required mobility for their mechanical hands. Thus the structure of the finger and the power transmission method for the mechanism find different methods. In [6], individually powered, articulated digits driven by and linked to its own 6V actuators are used to obtain the required mobility. Crisman et al. [9] introduced a hand design with link based finger design. Its power transmission is via cables run through the structural links of the finger mechanism. In [11], Mass et al. introduced a finger mechanism with three phalanges connected together with pulleys. Each pulley is driven by a wire in order to generate the flexion of the finger whereas extension of the finger is provided by the torsional springs attached to the phalanges. Spring hand [12] also consists of a finger mechanism based on structural links where the power is transmitted via cables. In order to obtain the grasping adaptation the finger design consists of two linear springs. Krut et al. [14] introduced a force–isotropic finger mechanism based on cam-tendon mechanisms. Finger mechanism is capable of generating 2DoF with single actuator. More details on the mechanical designs of hand prosthesis can be found in [20]–[22].

Next section of the paper presents the proposed finger mechanism.

III. UNDER-ACTUATED FINGER MECHANISM

Cross bar mechanism (CBM) is one of an already employed mechanisms for a finger design [23]. However, the design in [23] can only be used for a finger with two joints. Thus the design in [23], generates the motion at the MP joint and at a single IP joint. However, an anthropomorphic design of a finger contains three joints as the human fi-
The angular arrangement of the mechanism is mainly determined by the link lengths. Thus, only a single configuration of joint angles is satisfied for a given set of link lengths. Therefore, the mechanism is unable to facilitate the configuration of joint angles is satisfied for a given set of flexion/extension of the finger. Therefore, the mechanism is unable to facilitate the bending of the digit. In order to derive the kinematic equations, the angular arrangement of the mechanism is shown in Fig. 3 (a). The motor is connected to the link 4 rigidly. All links are connected together by pin joints. When motor is rotating it drives the link 4 and power is transmitted to link 2 and 5. Link 2 transmits power to link 1 and 3. Link 5 also transmits power to link 3. Thus, all links are driven by the motor. Link 1, link 2 and link 3 act as the three phalanxes of the finger. When motor is actuated these three links rotate about their pin joints and generate the flexion/extension of the finger.

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Accordingly link 4 and link 5 (see Fig. 3 (a)) are replaced with two links consist of passive prismatic joints. The introduced link with the prismatic joint and the spring is shown in Fig. 3 (b).

The translation section of the passive joint is supported by a compression spring which makes sure the modified mechanism does not move freely. When handling different geometries, the change of the link lengths ensures the different joint angles of the finger to adopt the geometries. Further, the consideration of the mobility is also an important design criterion. It is possible to compare the two configuration of the modified CBM using Grubler-Kutzbach criterion [24] for a planar mechanism.

\[ F = 3(n - j - 1) + \sum_{i=1}^{j} f_i \]  

where \( n \) is the number of links, \( j \) is the number of kinematic pairs and \( f_i \) is DOF of the \( i^{th} \) pair.

For the initial configuration without length varying links \( n=5, j=7 \) and \( \Sigma f_i = 7 \). Therefore, the DoF of the mechanism is equal to 1. Thus, without length varying links the mechanism is capable of generating only one motion with a fixed set of joint angles. For the modified configuration with introduced length varying links \( n=7, j=9 \) and \( \Sigma f_i = 9 \). Therefore, DoF of the mechanism is equal to 3. Thus, with introduced links, the mechanism is capable of generating 3 different DoFs. Accordingly, a single degree of actuation generates 3DoF for a finger. Therefore, the proposed mechanism follows the concept of under-actuation in its architecture. Fig. 4 (a) shows a finger design based on the proposed modified CBM. Here, two length varying links are placed inside the two phalanxes, proximal and middle. The placement of the two springs to the internal sliding joint is shown in Fig 4 (b). The mechanism is driven by the internal link attached to the shaft. The shaft is connected to the palm through bearings and is connected to the motor through a gear. Mechanically, when an object comes in contact with distal phalanx or middle phalanx two internal links get contracted. Thus the joint angles are adjusted according to the geometry of the object. Next section of the paper presents the kinematic analysis of the proposed mechanism.

### IV. KINEMATIC ANALYSIS

Fig. 5 shows the schematic link configuration of the proposed finger design. In the figure links DE, CEG, FH, AC and BF correspond to the links 1-5 respectively in Fig. 3. As shown in Fig. 5, \( \alpha \) is defined as the variable angle between the vertical axis and the link DE. \( \beta \) is the variable input angle between the vertical axis and link AC. \( \delta \) is defined as the variable angle between link BF and the vertical axis. \( \sigma \) is a variable angle between CE and vertical axis and \( \lambda \) is the variable angle between the EG and horizontal axis. \( \mu \) is the constant angle between CE and EG. \( \vartheta \) is the variable angle between the link FH and the vertical axis. In order to derive the kinematic equations, triangle of \( \Delta ACX, \Delta BMD, \Delta CZE, \Delta DEY \) and \( \Delta BNC \) are used.

Thus following equations can be obtained by solving the equations for the geometrical relationships of the above triangles.

\[ -C\cos \alpha = AC \cos \beta - AD - DE \cos \alpha \]  

\[ C \sin \sigma = DE \sin \alpha - AC \sin \beta \]  

\[ -F \cos \delta = GE \sin \alpha + BF \cos \delta + NZ \]  

\[ FG \sin \theta = GE \cos \lambda + MV - BF \sin \delta \]
Using the resulting equations, (2), (3), (4) and (5) of the kinematic analysis, a MATLAB model is created to obtain the relationships between the input angle and the joint flexion angles. The model can be used to find the range of motion of each phalanx. Fig. 6 shows the ranges of angle of flexion of each phalanx with rotation angle of main shaft. The upper boundary of the hatched area shows the maximum achievable angular variation with passive adaptation and the lower boundary shows the minimum angular variation. Accordingly, both PIP joint and DIP joints are capable of generating variable joint angles in the range of hatched area for a given value of MP joint angle. Thus middle phalanx and distal phalanx are capable of arranging in variable angle positions. Therefore, the proposed mechanism is capable of facilitating a prosthetic finger to be operated within the range of the angular variation shown in graphs, in order to grasp objects with different geometries.

Further, degree of adaptation \( \nu \) is introduced as a parameter to evaluate the performance of under-actuated finger designs. It measures the ratio between, range of angle of a phalanx can vary at a given metacarpophalangeal (MP) joint angle \( \delta \theta \) and MP joint angle \( \theta \). If degree of adaptation is denoted by \( \nu \),

\[
\nu = \frac{\delta \theta}{\theta}
\]  

\( \nu \) is used as a parameter to give an idea about the effectiveness of the adaptation mechanism. It shows the ability of a finger joint to adopt according to the different geometries. Higher the value of the parameter, higher the adoptability of the finger joint will be.

For an instance, in Fig. 6 (c) at MP joint angle of 60 the finger mechanism is capable of varying the position of the distal phalanx from 100 deg to 180 deg. Thus, the finger has the capability of handling any geometry within this range of angular position for the distal phalanx. Further, Using (6), instantaneous value of \( \nu \) at MP angle of 60 can be obtained for the distal phalanx. Accordingly, \( \delta \theta = 80 \) and \( \theta = 60 \). Therefore \( \nu = 1.3 \). Similarly obtained \( \nu \) results are shown in Fig. 7 for the index finger.

\[\text{Fig. 5. Schematic link configuration of the proposed finger design for kinematic analysis}\]

\[\text{Fig. 6. (a) Angular displacement of proximal phalanx, (b) Angular displacement of middle phalanx, (c) Angular displacement of distal phalanx.}\]

\[\text{Fig. 7. Velocity analysis (a) Link schematic diagram for velocity analysis}\]

It rapidly converges to a fixed value within first 10deg of the MP joint angle. \( \nu \) for distal phalanx is \( \nu_1 = 1.3 \) and for middle phalanx is \( \nu_2 = 0.34 \).
Fig. 8. A sequence of grasping at fingertips by an under-actuated finger (a) approaching motion; (b) distal phalanx in contact; (c) change of the DIP angle; (d) change of the PIP angle.

Fig. 9. Velocity analysis (a) Link schematic diagram for velocity analysis. (b) velocity diagram

Applying Sine rule to the triangle $adx$,
$$\frac{ad}{\sin(\theta-\sigma)} = \frac{ax}{\sin(\alpha+\sigma)} = \frac{dx}{\sin(\alpha+\theta)}$$

Applying Sine rule to triangle $ecx$,
$$\frac{ec}{\sin(\theta-\sigma)} = \frac{ex}{\sin(\delta-\sigma)} = \frac{cx}{\sin(\delta-\sigma)}$$

Solving (10) and (11) with relevant geometrical relationships angular velocity of link EF can be found.
$$\omega_3 = \left(\frac{1}{y_2} \times \frac{\sin(\alpha-\beta)}{\sin(\beta+\theta)} \sin(\theta-\sigma)\right) \times \frac{\sin(\theta-\sigma)}{y_3 \sin(\delta-\sigma)}$$

DISCUSSION AND CONCLUSION

This paper proposed an under-actuated mechanism to be used for a finger of hand prosthesis. Thus, a cross bar mechanism was proposed to realize the finger flexion/extension during ADL. The modification proposed for the mechanism allowed grasping adaptation while functioning. Further, Degree of Adaptation, $\nu$ was introduced as a performance evaluation parameter for under-actuated hand mechanisms. Values of $\nu$ for the proposed finger mechanism rapidly converged to a fixed value within first 10deg of the MP joint angle and values of $\nu_1=1.3$ for distal phalanx and $\nu_2=0.34$ for middle phalanx were obtained. Accordingly, with the MP joint angle the adaptability of the finger mechanism increased at a constant value. Hence, the under-actuation has been achieved while maintaining the adoptability of the joint angle according to the grasping object. Mobility analysis and kinematic analysis based simulations were carried out in order to verify the effectiveness of proposed mechanism. Mobility analysis proved that the mechanism is under-actuated. The simulation result also showed that the angular positions of the finger phalanxes are capable of adopting according the grasping object.

REFERENCES


