Design Development, Fabrication, and Preliminary Specifications of Multi-Fingered Prosthetic Hand

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Abstract—The study has developed the previous design of an artificial anthropomorphic humanoid hand and accustomed it as a prosthetic hand. The main specifications of this design are determined. The development of our previous design involves the main artificial hand's parts and subassemblies, palm, fingers, and thumb. In addition, the study presents an adaptable socket design for a transradial amputee. This hand has 3 fingers and thumb. It is more reliable, cosmetics, modularity, and ease of assembly. Its size and weight are almost as a natural hand. The socket cavity has the capability for different sizes of a transradial amputee. The study implements the developed design by using rapid prototype and specifies its main specifications by using a data glove and finite element method.

Keywords—Adaptable socket, prosthetic hand, transradial amputee.

I. Introduction

NATURAL hands are the vital organs that humans have [1]. The human hand with more than 27 Degrees of Freedom (DOF) and has a unique musculoskeletal structure. The fingers are connected to the palm with metacarpophalangeal (MCP) joints. These joints have two DOF i.e. flexion-extension and abduction-adduction, whereas the remaining two joints of the digits have only one DOF [2].

Artificial hands are divided into two main categories: robotic hands and prosthetic hands, with different design requirements and constraints. Robotic hands are not necessarily anthropometric and can have many DOF with complex control methods. On the other hand, prosthetic hands have strict controls over their design. They should be anthropometric with natural kinematics and cosmetics [3].

The inspiration of the design at two categories has been taken from the human hand. The weight of the hand is important when it has to be used for rehabilitation purposes, whereas in industrial applications the weight is not an important factor [1].

The increasing demand of hand prosthesis to overcome natural hand losses is rising. The design and development of artificial hands are very promising in recent times; although, creating a multi-fingered anthropomorphic robotic hand is a challenge [3]. There is a need for a new design, which conforms to the hand prosthesis constraints and can be produced for wide commercial use. They should enable the amputee to perform the necessary activities of daily living (ADLs) with appropriate speed and force. They should be

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lightweight, operate silently, and be easy for the amputee to control. Finally, they should be affordable to a large number of the amputee population [3].

The main key to satisfying these objectives and constraints such as lightweight and affordability is the use of advanced or smart materials, such as Shape Memory Alloys (SMAs) to power the joints of a prosthetic hand, and other dexterous robotic hands. A modular approach is taken in the design facilitating ease of manufacture and assembly, and more importantly, also allows the end user to easily replace SMA wires in the event of failure [3], [4].

The recent researches focused on using smart materials, design and develop, the multi-fingered artificial hand that works as a prosthetic [5]-[7]. The ability to mimic functional motions of biological hand, especially in handling complex objects, was achieved in the study of Ahmed [6].

The dexterous grasping is a paramount parameter to handle complex object. To achieve this parameter, the hands used compliant mechanisms or soft robotic technology. Another advantage of this technology, the hands were robust to impact and blunt collisions, inherently safe, and not affected by dirt, dust, or liquids. Furthermore, the hands were simple and inexpensive to manufacture [3], [8].

A study developed mechanisms that encompass both flexion-extension and abduction-adduction for all three fingers located on the palm opposite to the thumb [2]. Development of the whole prosthetic hand system or specific part was interesting for many studies such as [9]-[13].

The author presented two studies related to the prosthetic hand design [3], [14]. Khefa hand design was the first study as shown in Fig. 1 (a). It had three fingers and a thumb and was actuated by SMA actuator with a cooling system to accelerate the speed of its fingers. The design of the palm was inspired from the curves of the natural hand. Khefa had 11DOF that were included in the fingers and thumb [3].

The construction design of another prosthetic hand was the interesting point of the second study. This hand had nine DOF. Two of them were intended for the palm. In addition, the study added socket in the spring shape that had the capacity to expand its diameter. Its fingers were behaved as a similar voluntary opening hand [14].

This study is extension and development of the Khefa design [3]. Both of them have the same degree of freedom, the number of fingers and SMA actuator. This hand is categorized as a voluntary closing hand.

Improving Khefa appearance, the ease of finger assembly and to minimize palm parts motivates the author to present this study. Fig. 1 shows the comparison and improving the

design of the new and old design. The adjustable socket design for a transradial amputee is another interesting point.

Discomfort in prosthetic sockets continues to be a critical challenge faced by both prosthetics and amputees. Existing sockets tend to have a hot and humid climate and some sockets are difficult to don and doff [11]. There were some design proposals to overcome those limitations. The WILMER open socket is adjustable but looks bulky [11].

Another limitation was the socket size and shape. It was different from amputee to another according to amputee cutting level [11]. The socket designs varied from design to another. They related to the cutting level of the arm or leg.

Kendall et al. developed a prosthetic hand for transradial amputees [15]. There was a study for designing socket to overcome the excess heat problem or pressure distribution in the socket to solve the issue of patient discomfort. [16]

The study designs the palm and socket as one integrated part to fit the hand with the any size or shape of the forearm of a transradial amputee. The compliant mechanisms and hinges are utilized to design the socket and adapted the height and breadth of its interior cavity.

The experimental work includes fabricating the mechanical to fabricate of the developed hand. The performance of the fingers through gripping is determined by data glove.
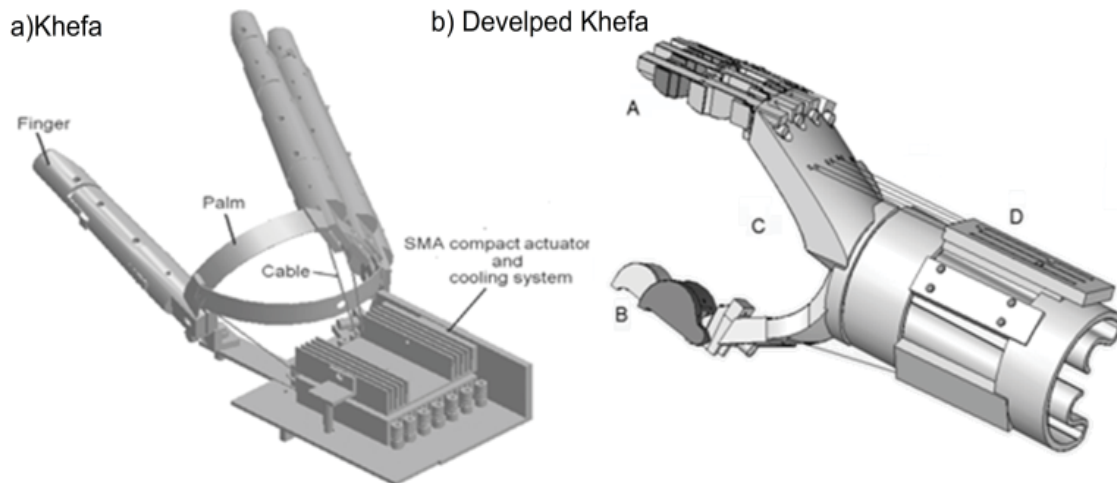

Fig. 1 Development and old Khefa hand designs

II. DESCRIPTION OF THE DEVELOPMENT DESIGN

This section describes the development design of Khefa. Fig. 1 (b) illustrates the development of Khefa and its effect on its appearance. A, B, C, and D, as shown in Fig. 1 (a) are represented finger, thumb, integrated palm and socket, and the SMA actuator, respectively.

The new design of the finger, the thumb and the new way to assemble are described. Also, the flexure hinges design of the adaptable socket and the palm construction is explained in this section. To locate the actuator that is represented as portion D and the method to attach it with a transmission wire.

A. Finger Design

The underactuated finger with anthropomorphic grasping function was the interested points for many types of research [3], [10], [14]. The finger in this study is categorized by an underactuated finger that means one actuator moves two joints or more. The lengths and widths of the fingers resemble that of the natural index finger and the transmission wire are routing as an FDP tendon.

The main modifications of the finger design are related to stiff parts shape and the finger fixation to the palm. Fig 2 (a) illustrates the final assembly of the finger. It has four types of stiff parts (Type A, B, C and D). The sequence of assembly for the finger is illustrated in the exploded view in Fig. 2 (b). The

numbers on Fig. 2 (b) is represent the assembly sequence order.

The compliant mechanism is the start part (1) then gathers the stiff parts with it from down to up (2, 3, 4, and 5), as shown in Fig. 2 (b). Finally, insert the transmission wire through the holes of the stiff parts. The finger transmission cable was the same as Khefa and mimics the FDP tendon through the holes in the stiff parts, as shown in Fig. 2 (a) [3]. Furthermore, the exploded view explains the gathering way and arrangement of the stiff parts with the compliant mechanism. The stiff parts had an opening side to assemble with the compliant mechanism side by side. The finger is more facilitating to ease manufacture and assembly, and also allows the end user to easily replace parts in the event of failure, than in the developed Khefa. The main finger dimensions are same Khefa's finger [3].

Thumb design contains three stiff parts (Type B, C and D) with the larger width dimensions to increase the opposition and contact area through grasping. It has two DOF.

Fig. 2 (c) illustrates the rear view of the finger after assembly and the way to prevent the finger from extending and interfering between the stiff parts. The stiff parts had a recession, engraved and cutout zones, as shown in Fig. 2 (d) to restrict finger movement except the flexing and ease assembly.

The A, B, C, and D stiff part types are illustrated their construction in Fig. 2 (d). Portion (a) is aiding the stiff part to rotate around another digit. Stiff parts type B and C and D have a portion (c) that represents the recess within the stiff part to insert stiff parts. It restricts the longitudinal movement of the digits and aids to assemble.
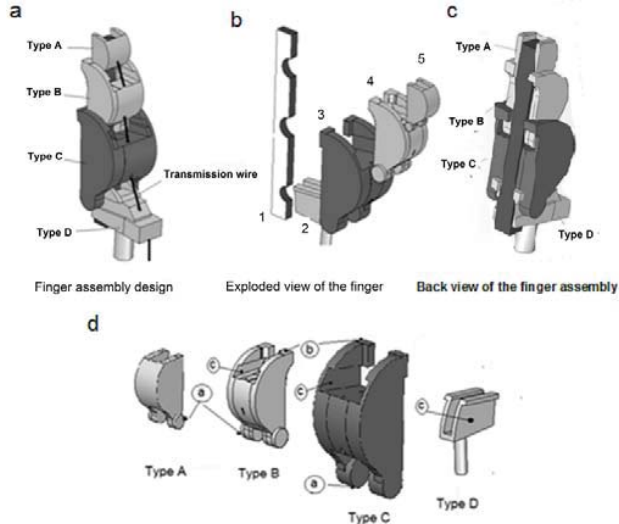

Fig. 2 Finger assembly and their stiff parts design

The finger extension would be prevented by portion (a) that is shown in Fig. 2 (d), as to deter or block in stiff parts (Type B, C, and D). The final stiff part D, as shown in Fig. 2, has two roles, mimicking the metacarpal joint with one degree of freedom and fixing the fingers within the palm.

B. Palm and Socket Design

Instead of the many parts that were incorporated, such as in the preceding palms of Khefa, the palm and socket design is presented as one integrated part, as shown in Fig. 3. The new palm design and its arches mimic Khefa, and it is the arches that aid grasping [3], [18].

The main two palm arches are illustrated in Fig. 3. The first arch is distal transverse arch concave curvature that was formed at the metacarpal heads of the index, middle, ring and little fingers. Another oblique arch is concavity formed by the opposable thumb with the fingers.

Arch A mimics the distal and arch B mimics oblique arch as shown in Fig. 3 (a). The developed palm satisfied these arches in one part. In addition, the palm has holes on the top of the palm to fix the fingers firmly, as shown in Fig. 3 (a).

The Palm-Socket part has three types of hole. These are the holes to aid in assembling the fingers with the palm, Type A-holes, for passing the transmission wires through them to attach with an actuator on the designed socket, and type B holes for fixing the actuator onto the forearm of the prosthetic hand. Fig. 3 (b) illustrates the location of all the holes on the palm-socket part. The socket length L1, initial socket breadth L2, and the maximum palm width L3 are shown in Fig. 3 (c) and their values in Table I.
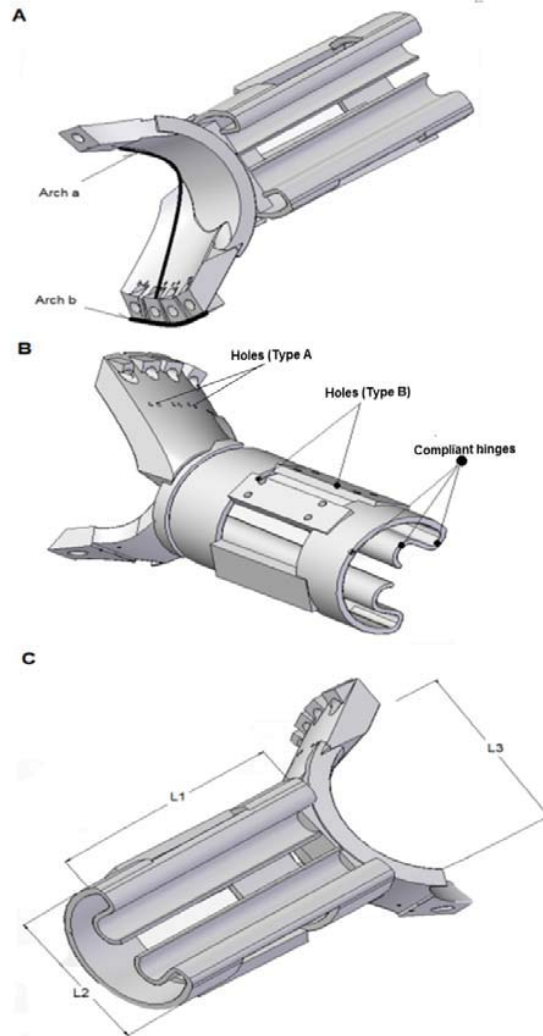

Fig. 3 The main features of the Palm-Socket module

The study presents socket design could be adapted for any different amputee cutting level and any size. This socket is classified as a transradial socket. Fig. 4 shows the socket design and its opening end. The augmenting and narrowing of the gap would be controlled by circular compliant hinges that have the following radiuses R1, R2 and R3, as shown in Fig. 4. Furthermore, the compliance distribution design to alter the inner cavity size of the socket according to the residual limb of an amputee.

The socket has three types of circular flexure hinges. The circular type R1 would be adjusting the width of the socket cavity. Both the circular type R2 and R3 vary the inner cavity height. The main geometrical parameters that effect on the total compliance of the socket hinges are shown in Fig. 4 (b). The compliance or capacity of the rotation of the non-symmetrical circular hinge around a z- axis that was induced by moment in the z-direction $C_{i\theta z - Mz}$ will be determined by [14]:

$$C_{i,y} - _{M_z} = \frac{12R_i^2}{EL_1(R_i+t)\sqrt{(t^5(2r+t)^5}}(3R_i^2+4R_i^2+4R_it+2t^2)\sqrt{t(2R_i+t)}$$

$$+3R_i(R_i+t)^2\left[\arctan\left[\frac{R_i}{\sqrt{t(2r+t)}}\right]\right]+\frac{\pi}{2}$$

$$C_{i\theta z - Mz} = \frac{C_{i,y} - _{Mz}}{R_i}$$

where i, R_i, t, L_1 and E are represented the circular hinge type, the radius, thickness, the length of the socket and a Younge's modulus, respectively. Table I shows the main dimensions of the palm and socket module and the geometric parameters of the flexure hinges. Fig. 4 shows the interior view of the socket was made of plastic by using rapid prototype.

TABLE I
MAIN DIMENSIONS OF PALM AND SOCKET

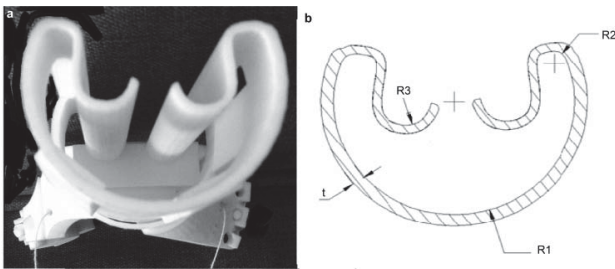| Symbol	Quantity	(mm)
R_1	Flexure hinge radius 1	46
R_2	Flexure hinge radius 2	5
T	Socket wall thickness	5
L_1,L_2,L_3	Lengths of the socket and palm	175,100,120

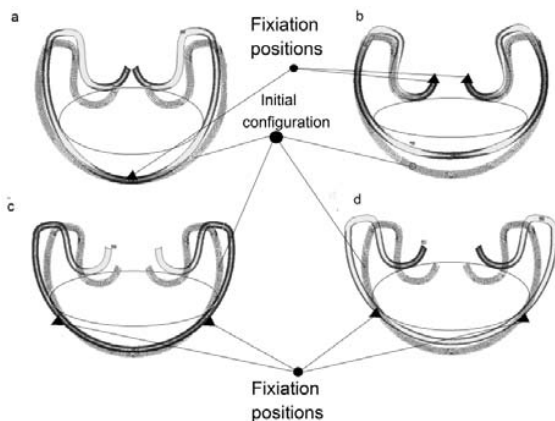Fig. 4 Physical interior view and the radiuses of the socket flexure hinges

Fig. 5 FEM simulations of possible expanding capabilities of the socket

Finite element method (FEM) is utilized to simulate varying the interior cavity sizes. Fig. 5 illustrates the four possible socket configurations and their capabilities in order to adapt with any residual limb. The fixation positions would be varied from one configuration to another. At the opening ends of the socket, at the center or at the both sides of the outer wall of the socket, are represented as black triangles.

There are configurations to increase the height only and maintain or decrease the width. Other configurations are decreasing the width and height of the socket at the same time or maintaining the height dimensions.

C. Actuator Module

The developed hand used the SMA compact actuator that was used in previous design Khefa [3], [17]. The study located the actuator module on the designed socket D, as shown in Fig. 1. This placement of the module and this of the configuration, simplify the SMA wires replacement through maintenance, because the SMA module was placed outside the hand and attached with transmission wires that passed through the finger and palm, as shown in Fig. 1. SMA encounters the surrounding air and aids in cooling.

D. Prototype Fabrication

The prototype was fabricated using Rapid Prototyping (RP) technique. RP is an advanced technique which utilizes automated fabrication of physical model or prototype from computerized data or CAD system for visualization, testing, and verification. It works by forming the desired shape by adding or removing layers of material [2]. Fig. 6 (a) shows the picture of the prototype without the actuator.
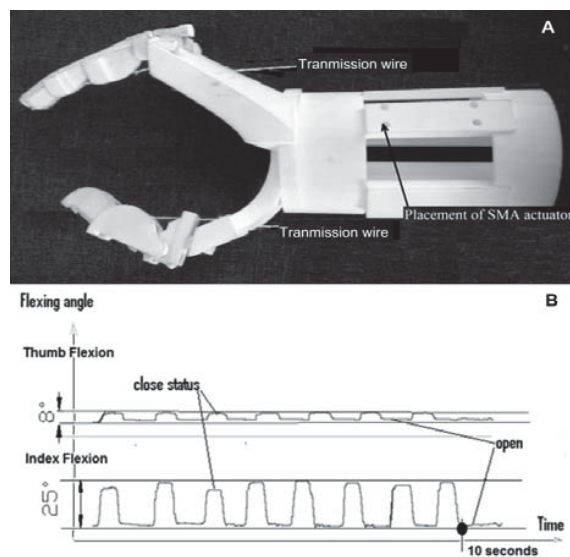

Fig. 6 (a) The prototype of the developed Khefa (b) The recorded data of index and thumb through grasping via Data glove

E. Experimental Work

The study used data glove to determine the flexing rate of the fabricated fingers (index and thumb) of the developed hand through opening and closing without load. Table II shows the main specification of 5DT Data glove that was used in the experimental work [19]. The used data glove is made by 5DT Corporation. It has five sensors for each finger that sense the flexing angle of the second joint of the thumb and index fingers [19].

The study uses the same SMA actuator system that was implemented and experienced in previous study [17]. According to the design, the transmission wires of the index and thumb fingers of the implemented parts, as shown in Fig. 6 (b), are attached to this actuator.

The recorded data are acquired for the thumb and index fingers at Pinch gripping state. They are depicted data glove output through moving the fingers eight times repeatedly, as shown in Fig. 6 (b). The opening and closing status of the fingers are illustrated in the Fig. 6 (b). The study specifies the opening and closing speed of the developed hand from these data.

TABLE II
DATA GLOVE SPECIFICATIONS

Specifications	5DT Data Glove
Material	Black stretch lyrica
Flexure sensors	12-bit A/D (typical range 10 bits)
	5 sensors in total
	1 sensor per finger, measures average of
	Knuckle and first joint

III. RESULTS

Fig. 5 shows the various configurations of the interior cavity of the socket by using FEM. The maximum augmentation of the socket cavity height and breadth attain to 20% and 18%, respectively. These incremental ratios relate to that of the early configuration of the socket without preload. There are different configurations of the socket at contraction status and when the socket cavity diminishes in height and breadth. The contraction rate for breadth and height are 20% and 14%, respectively.

The total mass of the implemented developed hand with the socket does not exceed 400 grams without a battery and has maximum opening span distance is 130 mm.

The finger flexing rate of the fingers through opening and closing were illustrated in Fig. 6 (b). The closing and opening speeds reach to 130 deg/s and 100 deg/s, respectively, for the fabricated index finger. For the opposable thumb finger, the closing speed is 85 deg/s and the opening speed is 70 deg/s.

IV. DISCUSSIONS

The study describes developing the prosthetic hand design and specifies the preliminary characteristics of this design. The developed hand resembles the natural hand in weight, [3] and more cosmetics than Khefa our previous design [3].

The discrepancy of this design is related to stiff parts shape, and simplified the way to assemble than the Khefa. The adaptable socket design introduced many configurations of the interior cavities. It has expansion-contraction abilities more than only circumradial expandability for the spring socket of the voluntary closing hand [14].

SMA wires and the compliant mechanism of the fingers have larger failure probability. This design version eases the assembly and increases the maintainability of the failure parts than the Khefa hand [3].

Experimental work and FEM specify the mass of the developed hand, the flexing rate of the finger and thumb, the maximum opening span and the incremental or contraction ratios of its socket. The range of geometric cavity size is suitable for the different residual stump of the transradial amputee.

The closing speed is slightly faster than the opening of the fingers. The made thumb is slower than the index finger. The flexing speed is defined at one grasping type only. The average finger speed of the developed hand is within the speed of the most common commercial prosthetic hand [15].

V. CONCLUSIONS

This study describes the development design process of the prosthetic hand and fabricates it. Multfingered, higher modularity, light weight, easily assembly, fewer parts and cosmetic shape are the predominant characteristics of this hand. The finger speeds are similar to branded and widely available commercial prosthetic hands. The additional attribute for this design to adjust the hand prostheses for any atransradial amputee size is the socket design. The expansion and reduction ratios of this design can be provided to fit with any amputee's stump size.

VI. FUTURE WORK

The study will apply the prosthetic hand with different transradial amputees to assess it clinically and measure its ability to grasp different objects. In the future, studies could use different actuators with this prosthetic, alongside the SMA actuator.

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