Mechanical Design of an Anthropomorphic Prosthetic Hand for Shape Memory Alloy Actuation
Ahmed M. El Kady, Ahmed E. Mahfouz and Mona F. Taher

Abstract—This paper presents the mechanical design for an anthropomorphic prosthetic hand which is one of the main components of an upper limb prosthesis. The design includes the pathways for the finger flexing cables which can be actuated using shape memory alloy (SMA) wires. Two prototypes were implemented and evaluated. The second prototype showed advantages of improved grasping capabilities and a more natural shape of the fingers. The design is based on simple mechanisms which can be incorporated in the limited space available. It utilizes fewer cables for finger flexion thus requiring fewer control inputs and simplifies the required control scheme. This results in a hand which is more affordable, lighter in weight, easy to control and requiring less power consumption.

I. INTRODUCTION

Amputation of the upper or lower limb causes severe disruption of an amputee’s life, both physical and psychological. In order for the amputee to return to being a productive individual, it is essential to wear a prosthesis. The prosthesis should restore as much of the lost function and appearance as possible. It should be simple to use and control; otherwise the amputee will discontinue wearing it. Finally it should be affordable, easy to manufacture and maintain.

The main components of an upper limb prosthesis are the mechanical hand or gripping terminal device, the actuator, the input signal for control, the control system and the power supply. Most prostheses currently use myoelectric control. Surface electromyographic (EMG) signals from the amputee’s residual muscles are detected, processed and used for control. The challenges that remain under investigation are the mechanical design of the hand, the choice of actuator and its control system.

For many years there have been widely used commercial myoelectric hands such as the Otto Bock SensorHand™ (Otto Bock HealthCare GmbH) and the Motion Control Hand (Motion Control, Inc.). In these hands, the fingers and opposing thumb are rigid with fixed curvatures. The hand is closed by a motor providing one degree of freedom (DOF) and limited unnatural grasp. More recently, the i.LIMB® hand (Touch Bionics) was introduced commercially. It is a myoelectrically controlled anthropomorphic hand with five articulated fingers. The fingers are actuated by micromotors in each joint and it is a very expensive product.

A comprehensive review of the mechanisms and actuators used in prosthetic hands still in the research phase was published by Del Cura et al. [1]. Anthropomorphic designs, which follow human anatomy, provide more natural prehension (grip) patterns. These have articulated fingers and hence more DOF. A system of cables (tendons) and actuators is used to cause finger flexion [1]. The problem with increasing the DOF is the need for more control inputs if each DOF is to be separately controlled. Underactuated mechanisms where the number of actuators is less than the DOF provide a more adaptive and natural grasp and require fewer inputs [2, 3]. Several different types of actuators have been used in prosthetic applications. These include motors, hydraulic actuators, piezoelectric actuators, shape memory alloys (SMA) and contractile polymer gels [1]. SMA wires have the ability to contract when heated (activated) and thus are sometimes called artificial muscles. They show promising results as prosthetic actuators because of their low weight and silent operation.

There are several research groups working on anthropomorphic hands using various actuators, and others experimenting with SMA actuators, but to date there is no commercially available hand which combines these two design features. Initial experiments on articulated fingers have been reported [3, 4, 5]. These investigate kinematics, cable pathways, choices for actuators and control strategies. In 2001, Schultz et al. [6] presented a very lightweight artificial hand that approximates the manipulation abilities of a human hand very well. It is a five fingered hand driven by a powerful small size flexible fluidic actuator. The Rutgers hand was developed in 2002 [4, 7, 8] This is a five fingered anthropomorphic hand where each finger has two artificial muscle bundles, one for flexion and the other for the recovery force. Carozza et al. developed the Spring hand in 2004 [3]. This is a three fingered hand actuated by cables and a motor. A key feature of this hand is the underactuated mechanism for finger control which results in more adaptive grasping. A four fingered hand with embedded SMA wires was developed in 2007 [9]. In 2009, Zajdlik presented a five-fingered motor driven prosthetic hand [2] based on the idea of using less actuators than joints while keeping the adaptability and functionality of the mechanism.

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In this ongoing work a complete system for an improved affordable upper limb prosthesis is being designed and developed as a prototype for local production. It consists of an anthropomorphic biomimetic mechanical hand actuated using SMA wires, a control system for the SMAs, surface EMG electrodes to be placed on the amputees residual muscles, a microcontroller for EMG signal processing and control of the prosthesis and a power source. This paper focuses on the mechanical design and implementation of the hand including the mechanisms used for finger flexion and extension. The hand has articulated fingers and is biomimetic meaning it mimics the kinetics and kinematics of the normal hand. It is actuated using a system of inextensible cables and SMA wires.

II. MATERIALS AND METHODS

The objective of the mechanical design is to have an anthropomorphic hand (similar in size and structure to the human hand) and kinematically accurate movement to fulfill normal grip requirements. This objective poses restrictions on the space available for mechanisms and actuators. The finger design includes a pathway for the passage of cables (tendons) which flex the fingers when pulled. These cables are actuated (pulled) using SMA wires (artificial muscles).

Anatomical lengths of an average adult male index finger are approximately 18 mm, 26 mm and 45 mm for the distal, middle and proximal phalanges respectively. The joint ranges of motion (ROM) are 90°, 100° - 110° and 80° for the meta-carpophalangeal (MCP), distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints respectively [5].

Two hand prototypes were implemented and tested. In both designs, the mechanical structure of the finger consists of 3 phalanges. The joints between them, PIP, DIP and MCP, are articulated with single DOF hinge joints. The MCP joint is constrained to a single DOF instead of the biological two for simplicity. There is a pin spanning the width of each joint, with a torsion spring to passively extend the fingers and open the hand. The spring also provides the bias force needed for the SMA wires to function. Each finger is flexed using only one inextensible cable passing through channels in the finger structure. The cables are then connected by crimps to the SMA wire actuators which provide the required finger flexing force when they contract.

A. First Prototype

In this prototype, the fingers were hand machined using Ertalon hollow tubes, a polymer which features high mechanical strength, excellent machineability and good electrical insulating properties [10]. All five fingers of the hand have the same structure and dimensions. Each joint is a single DOF revolute joint and consists of 2 interlocking hinge sections with a pin spanning the entire width. The hinge is shaped such that it provides mechanical stopping points which ensure that hyperextension of the joints does not occur. The pin is made of steel and has a 2 mm diameter and 20 mm length. All three phalanges have 2 mm diameter pin holes in both hinge sections.

The dimensions of each phalanx are as follows. The distal phalanx is 15 mm in diameter and 20 mm long from center of pin joint to tip. The main phalanx body is 15 mm in length. The middle phalanx is 15 mm in diameter, 30 mm long from center of pin joint to center of pin joint and has an overall length of 35 mm. The proximal phalanx is 15 mm in diameter, 45 mm long from center of pin joint to center of pin joint and has an overall length of 50 mm. The main phalanx body is 30 mm long. The hinge sections in all three phalanges are 10 mm long and 7.5 mm wide. The thumb is tilted at an angle 60° from the plane of the palm. It is at an angle of 24° (internally) from the vertical as shown in Fig. 1. These angles permit the thumb to travel across the palm as it closes to oppose the fingers.

The palm supports the mounting of the four fingers and the thumb. It is constructed of two parallel Plexiglas sheets of 4 mm thickness. The two sheets are 20 mm apart. Plexiglas was used for its light weight, electrical insulating properties and its machineability.

In each of the fingers the actuation cable is fixed to the proximal end. It runs in the 6 mm hole through the finger and comes out from the DIP joint. The cable then enters again through a small hole in the distal phalanx. The cable exits the finger at the distal end of the 6 mm hole. It is then pulled back along the outside of the finger and fixed on the surface of each phalanx using plastic rings.

B. Second Prototype

In this prototype, each finger consists of three interlocking segments and the thumb consists of two segments. The general external shape of the segments was based on a previously reported finger model [5]. The cross-sectional area of the segments progressively decreases towards the fingertip to mimic the tapered look of the natural finger as shown in Fig. 2. The joints are single DOF revolute joints connected by 3 mm steel pins. There is a torsion spring in each joint. The inner diameter of the spring is 4 mm and its body width is 3 mm. These springs provide the bias force needed for SMA contraction and also passively return each
segment to the relaxed extended position to open the hand. Spring dimensions are used to determine the spring constant. Solid models of the segments were drawn with Autodesk 3ds Max graphics software and prototyped using 3D printing, also referred to as Solid Freeform Fabrication. Fig. 2 shows the connected segments of the index finger with the lengths of the phalanges from joint to joint. In each finger, the cable is attached to the 2 mm hole in the distal phalanx then passes through a cylindrical pathway running along the center of all segments till it exits at the MCP joint. In order to obtain maximum joint rotation (flexion) with the small strains provided by the SMA wires, the cable is attached very close to the center of rotation of the DIP joint. This is at the expense of requiring a larger force for rotation due to the smaller moment arm. Cable excursion needed to fully flex the finger was measured and found to be 1 cm. The finger was flexed repeatedly and the force needed for full finger flexion was found to be 3.3 N.

Fig. 2. 3D Model of finger showing dimensions in mm.

The palm is constructed using two aluminium sheets 2 mm thick and 20 mm apart. Two identical fingers and the thumb are attached to the palm structure.

III. RESULTS AND DISCUSSION

In this work, two designs for the hand were constructed and evaluated. As described above, numerous prosthetic hands have been proposed in the literature with varying mechanics, actuators and control systems all inspired by the human hand. The question is how does one evaluate the performance of these hands quantitatively to be able to assess their effectiveness relative to each other and to the ideal human hand? Biagiotti et al. [11] addressed this issue regarding robotic hands and proposed several indices which refer to the degree of anthropomorphism, that is the resemblance with the human hand concerning aspect and mechanical structure, and to the level of dexterity, resultant from the kinematic configuration, the sensory apparatus and the control system. The anthropomorphism indices include size of different segments, kinematics of the hand and the contact surfaces involved in grasping tasks [11].

A. The anthropomorphic design implemented in this work was modeled on hand anatomy. The sizes of the finger and thumb phalanges are similar to standard anthropomorphic measures as described above. The shapes of the phalanges in the second prototype are closer to those of the human hand. In addition, modeling them using 3D printing had the advantage of early verification of product designs [12]. However the palm structure is not anthropomorphic and is under investigation to model and prototype an anthropomorphic design.

B. The kinematics and contact surfaces of the two prototypes were evaluated. The significance of sufficient joint flexion is the ability of the hand to fulfill one of the key design objectives which is prehension. In addition, maximizing the contact area between the hand and the object being grasped reduces the required grip force for proper prehension without slipping. The hands were closed using a force of 26 N. Maximum joint rotations were measured for both prototypes and are given in Table I.

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<th>DIP</th>
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<tr>
<td>First prototype</td>
<td>70°</td>
<td>70°</td>
<td>60°</td>
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<tr>
<td>Second prototype</td>
<td>55°</td>
<td>56°</td>
<td>90°</td>
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Previous authors have reported a ROM of 40° for the MCP and 40° for the PIP which is not sufficient but is the maximum they achieved [5]. The Spring hand has a rotation around the MCP joint of 45°, intermediate link 25.4°, distal link 15.5° and the authors observed that these values provide a natural flexion of the fingers and good grip [3]. The Rutgers hand provides maximum joint deflections of the first joint 77°, second joint 73° and third joint 88° [8].

The two prototypes presented here provide good cylindrical prehension patterns. They are shown grasping a cylinder with a diameter of 55 mm in Fig. 3 for the first prototype and Fig. 4 and Fig. 5 for the second.

Fig. 3. (a) CAD drawing of the first prototype grasping cylinder. (b) 3D Model of the first prototype grasping the same cylinder.

The second prototype has the advantage of an increase in the contact points between the object and the fingers,
resulting in a more secure grasp with less force needed from the actuator. The fingers would benefit from a layer of compliant material with a large coefficient of friction to possibly increase the contact area further and reduce the possibility of slipping. The space between the cylinder and the palm is consistent with a similar space when the human hand grasps a cylinder.

The use of cables and SMA wires for actuation rather than conventional motors results in a more lightweight prosthesis with silent operation. The second prototype weighs approximately 320 gm as compared to 450 gm for the Motion Control Hand and 460 gm for the SensorHand™.

In both prototypes, the three joints in each finger are flexed by only one cable compared to a separate cable for each joint as proposed in [8]. This mechanism provides a more adaptive grasp since the three joints do not necessarily rotate with equal angles as the finger wraps around an object. In addition, each joint is passively extended using the torsion springs as opposed to the push-pull activation where two opposing cables and SMA wires are used for flexion and extension [7, 8, 12]. These two design features essentially provide actuation with fewer cables thus requiring a simpler control scheme with fewer control inputs as well as less power consumption which are desirable features in a prosthetic hand. Finally, the pathway of the cable in the second prototype is internal to the finger which solves the problem of the cable crossing the joint during flexion and obstructing the space available to grasp the object. It will also allow the user to wear a cosmetic glove without hindering the cables.

Fig. 4. Model of second prototype grasping a cylinder

Fig. 5. Second prototype grasping a cylinder

IV. CONCLUSION

There are several research groups working on anthropomorphic hands, and others experimenting with shape memory alloys as actuators, but to date there is no commercially available prosthetic hand which combines these two design features. The mechanical design and prototyping of an anthropomorphic prosthetic hand which can be actuated by SMA artificial muscles is described in this work. The kinematics of the fingers and grasping ability were tested and confirmed. The hand is lightweight and operates silently. Extension of the mechanical design includes designing and prototyping an anthropomorphic palm structure which includes the natural arches of the hand. The significance of this ongoing work is to provide an affordable, efficient upper limb prosthesis for local production.

REFERENCES