

A Novel Monolithic Soft Robotic Thumb for an Anthropomorphic Prosthetic Hand

Hao Zhou¹, Alireza Mohammadi², Denny Oetomo² and Gursel Alici¹

Abstract— The thumb of a natural hand or a prosthetic hand plays a significant role in realizing a hand’s grasping and manipulation activities. This requires that mechanical design of a prosthetic hand should allow its thumb to perform both abduction/adduction and flexion/extension in order to mimic a natural hand’s grasping and manipulation abilities with a minimum number of actuators. In this work, we propose a novel monolithic soft robotic thumb for an anthropomorphic and transradial prosthetic hand. The thumb and the whole prosthetic hand were fabricated using a low cost 3D printing technology, with sizes comparable to those of real human ones but with much lighter weights. Based on the concepts of soft robotics and underactuation, the thumb shows significant mechanical compliance and performs well in power grasps, precision grasps and lateral grasps of different shaped and sized household objects. The soft thumb which has two modes of operation based on an innovative and compact mechanism, and one actuator only offers grasping versatility (capable of both abduction/adduction and flexion/extension). This novel thumb minimizes the number of actuators and reduces the corresponding requirement on space consumption (for housing its actuators) and power consumption, which are favorable features to develop low cost, low power and low weight prosthetic hands with intrinsic compliance.

Index Terms—Soft robotics, prosthetic hand, thumb, underactuation, 3D printing.

I. INTRODUCTION

Upper limb loss significantly impairs work-related skills, social capability and ability of individuals to undertake daily living activities (ADLs). For decades, numerous efforts have been made to develop novel and practical hand prostheses to help the people restore their limb loss, due to amputation or birth defects, as much as possible. Though body-powered prosthetic hands still serve a large population with an upper limb loss, robotic prosthetic hands with anthropomorphic appearances and functionalities, and

controlled through human-machine interface (HMI) have been receiving significant attention from prosthetic hand users [1, 2]. There are a few commercially available robotic prosthetic hands [3], e.g., iLimb (by Touch Bionics), Bebionic hands (by RSL Steeper), Vincent hand (by Vincent System), Michelangelo hand (by Otto Bock), etc. Moreover, there are a number of non-commercial prototypes that have been designed and developed by different research groups [4-11]. As a fast-growing discipline of robotics, soft robotics can provide robotic solutions with safe interaction with their environments due to intrinsic compliance and adaptive interaction [12], which are essential for the design and effective operation of a prosthetic hand. In one of the earliest attempts, a soft robotic finger made of a 3D printed elastomer with three flexure hinges as its revolute joints has been proposed [13]. The whole soft finger is featured as a monolithic structure and does not require any assembly for the joints’ movement, which is more cost-effective compared to fabrication of traditional robotic fingers. Besides, the soft finger does not require lubrication or maintenance and there is no friction loss for the joints, making it advantageous further [14]. Soft robotics is a promising approach for developing novel and functional prosthetic hands.

Mechanical design is critical for the development of a robotic prosthetic hand as it directly addresses several design parameters: weight, functionality, and cost (including both capital and maintenance expenses). Since a human hand is so dexterous with 27 degrees of freedom (DOFs), it is neither practical nor economical to achieve a full mechanical copy of its biological capability with current technology. The most common strategy for the mechanical design of a prosthetic hand is to recover the grasping ability for amputees as much as possible with a low cost, low weight and compact prosthetic hand.

It is widely reported that the thumb is responsible for over 50 % of a hand’s grasping activities [15]. The thumb’s opposability (opposing the thumb to the other four fingers) and strength is significant for a hand to grasp and manipulate objects. Although the thumb is so important and its moving modality is quite different from the other fingers’, limited studies are reported on the mechanical design of the thumb. There are quite a few modular designs still making the thumb identical to the other fingers except to place it in an opposed configuration [16], which greatly restricts the function of the thumb and consequently the grasping capability of the whole hand. In the literature about the thumb, Chang and Matsuoka

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proposed a kinematic model for their anatomically-correct testbed hand, in which thumb was designed to have three joints and five DOFs [17]. In another work by Chalon and the co-workers, a detailed methodology was introduced to develop the functional thumb with three joints and four DOFs, based on the knowledge of anatomy, rehabilitation and surgery for their robotic Awiwi hand [16]. Cotugno and the co-workers investigated the human thumb's reachability and compared it with that of two state-of-the-art robotic hands [18]. In the work by Wang et al., different thumb configurations with 4 and 5 DOFs were introduced and their performances were theoretically and experimentally evaluated [19]. All these studies intend to endow the robotic thumb with the same or at least very similar manipulating ability as its biological counterpart has. This design strategy can enable an artificial hand to realize a human hand's dexterity to a certain extent. It is definitely an excellent strategy for a robot's hand. However, it may not be practical for a prosthetic hand to have 4 to 5 DOFs for the thumb only. According to the statistics reported in [20], approximately 75% amputation is either transcarpal (61%) or transradial (12%) or wrist disarticulation (2%). Therefore, the space to accommodate all the actuators (including those for the thumb and the fingers) is quite limited, most of which is within the palm. Other considerations include weight requirement and financial affordability for a prosthetic hand, which is also quite related to the number of actuators. For the thumb in particular, one or two actuators are usually used in many commercial prosthetic hands or in-lab prototypes [3].

In this study, we propose a novel monolithic soft robotic thumb, which can generate two modes of operations corresponding to abduction/adduction and flexion/extension, respectively, but using a single actuator providing both modes of operation. The full design concept of the thumb, including the structures of the phalanges and the joints, is described together with the actuation mechanism. The proof-of-concept prototype was fabricated using additive manufacturing (so-called 3D printing) technology and its performance was experimentally evaluated.

This study pushes the limit for underactuation to generate two modes of operation for an already underactuated prosthetic finger, i.e. thumb. It provides a promising approach for the design and implementation of a robotic thumb, which consolidates the base for developing a next-generation anthropomorphic prosthetic hand based on soft robotics and 3D printing technologies.

II. OBJECTIVES

To make a robotic prosthetic hand practical and affordable, the widely employed approach is to functionalize a few commonly used grasps and gestures, by which the DOFs and the required number of actuators can be significantly reduced [21]. Among these identified grasps and gestures, the top three are power grasp (used for 40% ADLs), precision grasp (pinch or tripod grip, used for 30% ADLs) and lateral (or key) grasp (used for 10%) ADLs) [1, 22]. All of them require a well-functional thumb. To realize all of these three main grasps

with one prosthetic hand, a minimum of two DOFs is needed for the thumb so that it can be capable of both flexion/extension and abduction/adduction. To achieve two DOFs, some researchers developed a robotic thumb articulated with two actuators so that both DOFs could be separately controlled [4, 23]. Another approach is to use one actuator for flexion/extension while the other DOF (abduction/adduction) is manipulated manually, such as the case with the Bebionic hands (by RSL Steeper) [3]. The primary objective of this work is to provide the third alternative: controlling at least two DOFs of a robotic thumb using only one actuator. Since the thumb is actuated via tendons in this work, two tendon systems are employed to realize this objective.

Some desirable prosthetic hand indicators for the tip force and open-close time have been reported in the literature [3, 4]. As for the thumb particularly, the tip force of 25N is aimed and the time to finish the full movement for each DOF needs to be less than one second.

III. DESIGN

A. Basic configuration

As a self-contained prosthetic hand with actuators assembled in its palm, the space consumption and power consumption of the actuators should be minimum. So should be the number of actuators. Its mechanical design should find the balance between the simplification (i.e. compactness) and the functionality.

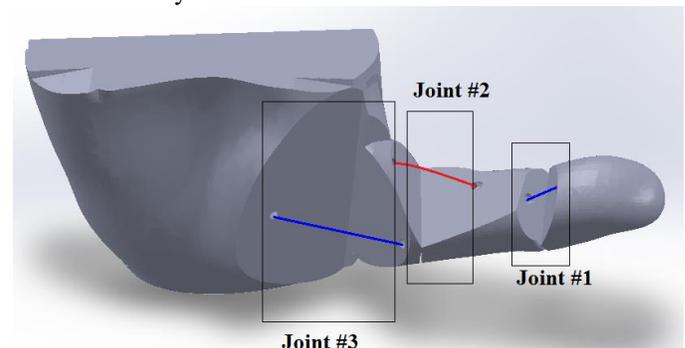


Fig. 1. The CAD design of a multi-joint soft robotic thumb (shown together with a hand palm), the tendons' routes inside the structure not shown.

Fig. 1 shows the computer-aided design (CAD) of a multi-joint soft robotic thumb together with a hand palm. The whole structure is monolithic, requiring no assembly. The total length of the thumb is 90 mm. Three flexure hinges are used for its three joints. None of these joints shares the same rotational axis. The thumb has three DOFs controlled by two tendon systems.

The presence of Joint #3 enables the thumb's palmar abduction/adduction. The rotational axis is at the connection of the palm and the thumb. With Joint #3, the thumb can change between the non-opposed position and the opposed position (relative to the fingers). The former is required for the lateral grasp while the latter is a must in the power grasp and precision grasp. Joint #3 simulates one DOF of the trapezoid-metacarpal (TM) joint of a real human hand. As is seen in Fig. 1, the thumb's initial status is designed to be at the non-

opposed position, pointing to the side of the palm. The range of motion (ROM) for Joint #3 is from 0 to 100°. At 100°, the thumb's tip is designed to face the middle finger. With this ROM, the thumb is capable of performing the commonly used precision grasps, e.g., pinch, tripod grip, associated with the movement(s) of the index finger and/or the middle finger.

The position of Joint #2 is between the TM joint and the metacarpal-proximal (MP) joint of a real human hand, located 20 mm away from Joint #3. Its ROM is from 0 to 90°, designed to achieve one DOF of the thumb's flexion/extension and enable the thumb to firmly tap the bent index finger for the lateral grasp.

Joint #1 is another DOF of the thumb's flexion/extension. It is located 33 mm from the tip of the thumb and 37 mm from Joint #2. It acts like a human thumb's distal-inter-phalangeal (DIP) joint. The ROM of Joint #1 is designed to be 0 - 60°.

Fig. 2 shows the cross-section of one typical joint in our thumb design. In our design, the flexure hinge is not located at the edge of the joint, which was adopted by some other reported soft fingers [13, 24]. Instead, it is positioned in the "middle" section of the joint. The advantage of this configuration is that the twisting at the hinge can be greatly improved. The prevention of twisting is important for stably holding an object since the finger/thumb may take loads not only in the normal direction but also in the tangential direction at the same time due to the object's weight. In Fig. 2, the thickness of the flexure hinge, t , is designed to be 2 mm. At the left-hand side of the hinge, a V-shaped notch is adopted to allow the rotation of the joint up to θ degree. Since the flexion of the finger/thumb is only to one direction, there is no need to have a symmetric profile at the right-hand side of the hinge. A 0.5 mm thick groove is carved to make the joint free for flexion and prevent the reversed rotation in the meantime. Another advantage of this configuration is that the possibility of buckling during flexion can be effectively lowered. A similar-shaped flexure hinge was adopted by the "Ada hand" by Open Bionics [25].

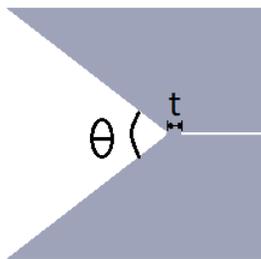


Fig. 2. Cross-section of one typical joint featured by a flexure hinge.

As the feature of a typical soft robotic system, the thumb's movement back to its original status (e.g., palmar abduction, extension) are achieved by the intrinsic elasticity of a flexure hinge, which acts like a torsional spring. As for the palmar adduction and the thumb's flexion, they are driven by the tendon actuation. Two tendons are employed to provide the thumb with two different moving trajectories. Joint #2 is

controlled by one tendon (highlighted in red in Fig. 1) while Joint #1 and Joint #3 are connected in series and controlled by the other tendon (highlighted in blue in Fig. 1). Both tendons are driven by only one actuator, an electric servo motor (Dynamixel XL-320).

B. Two-axis flexure hinge

For a real human thumb, the bone length ratio $\frac{TM-MP}{MP-DIP}$ is approximately 1.42 on average. However, this ratio is only 0.54 in our design. The position of Joint #2 is set to be much closer to the TM joint rather than the MP joint of a real hand. The reason for that is that Joint #2 is designed to act more like one of two DOFs of the TM joint. Therefore, Joint #2 and Joint #3 can be considered as a two-axis flexure hinge with non-located notches to function as a two-DOF TM joint. One DOF (Joint #2) is to achieve the lateral grasp and the other DOF (Joint #3) is to achieve the power and precision grasps. Two DOFs are not required for these grasps at the same time. Since they need to be able to work separately, they cannot be connected in series. Each DOF is connected and actuated by a separate tendon.

A two-axis flexure hinge has two axially-located notches. In other words, the primary axis and the secondary axis intersect at the center of the hinge. With this configuration, the flexure hinge needs to be slender in both the primary axis and the secondary axis since a relatively large degree of rotation is required in either of these axes for the thumb. When the flexure hinge is thin, the possibility of rotation out of the predefined axis (either the primary or secondary one) greatly increases because the net force on the thumb does not necessarily act along the predefined axis. Besides, the twisting may also occur at the flexure hinge with such a thin profile. With a non-located configuration proposed in this study, these concerns are effectively addressed. The stability and robustness of the thumb's motions can be improved. Therefore, a non-located configuration is adopted in our design rather than a collocated configuration.

C. Underactuation

As shown in Fig. 1, Joint #1 and Joint #3 are connected in series and the approach of underactuation is employed to control their rotations simultaneously. In the simplest design, Joint #1 can be eliminated and only Joint #3 remains for moving the thumb to the opposed position for the power grasp and the precision grasp. If this is the case, the thumb itself does not contribute to the grasping force. It acts like a supporting base. The active grasping force comes from the finger(s). Since an actuator has been exclusively allocated to the articulation of the thumb, it would not be fully utilized if it only produces kinematic contribution (moving the thumb to its position) and passively supports the grasps. Thus, Joint #1 is introduced in our design, which acts like a human thumb's DIP joint and enable the thumb to be flexed towards the grasped object. By this design, the thumb also produces active contribution to the grasping force.

Different from a finger's joints [13], the rotational axes of

Joint #1 and Joint #3 are on separate planes. Ideally, the thumb needs to make abduction/adduction and stop at the desired opposed position first by the actuation of Joint #3. Then the actuation of Joint #1 takes effect to generate active touch and exert pressing force onto the aimed object. However, the underactuation does not influence the joints separately but simultaneously. Without external influence, the relative movement of the joints reflects the combined effect of the lever arm at every joint and the relative stiffness of the joints. The tendon system reaches equilibrium when the moment acting on each joint becomes equal. To make the thumb's movement close to the desired movement pattern described above, the effective lever arm of Joint #3 is designed to be three times larger than that of Joint #1 while the stiffness of two joints are set to be similar.

The underactuation also provides compliance to the thumb, making it more adaptive to different shaped objects.

D. Modality selection

As discussed in Section II, power grasp, precision grasp and lateral grasp are three most common hand patterns to conduct approximately 85% of ADLs. For power grasp or precision grasp, the thumb needs to be in an opposed position to the finger(s) while it has to be in a non-opposed position to start a lateral grasp. To finish a lateral grasp, the thumb's flexion is required. Therefore, at least two DOFs needs to be provided to a robotic thumb and these two DOFs should be controlled separately. They cannot be connected in series and controlled by underactuation. Different from any current solutions, we do not use two actuators or use one actuator for flexion and manually switch the thumb between opposed and non-opposed positions. In this work, an innovative and compact solution is proposed to control of two DOFs of the thumb by using only one actuator.

As a soft robotic structure, the thumb utilizes its own intrinsic elasticity to return to its original position once the external force is removed. Take flexion/extension for an example. Only one tendon is required to function as either a flexor or an extensor. When the tendon is pulled, either the flexion or the extension is conducted. When the tendon is released, the opposite motion of the thumb is provided by the elasticity of the flexure hinge. Since an electric motor can rotate in two directions, each of rotation can provide actuation to an individual tendon system, which means the two tendon systems can be separately actuated by one electric motor. This is a simple, but a novel actuation concept.

The concept of actuation is shown in Fig. 3(a). In our design, the clockwise rotation (Top View in Fig. 3(a)) of the motor pulls one tendon (#2) to flex Joint #2. In order to prevent the clockwise rotation to pull the other tendon (#1) in the meantime, a certain length of Tendon #1 needs to be wound onto the pulley in the anti-clockwise direction before actuation. When the motor starts to rotate in the anti-clockwise direction (Top View in Fig. 3(a)) from its original position, Tendon #1 is pulled to actuate Joint #1 and Joint #3. Similarly, a certain length of Tendon #2 needs to be pre-wound onto the pulley clockwise for not being pulled in this situation. By

switching the rotation direction of the motor, the modality of the thumb's motion can be selected effectively.

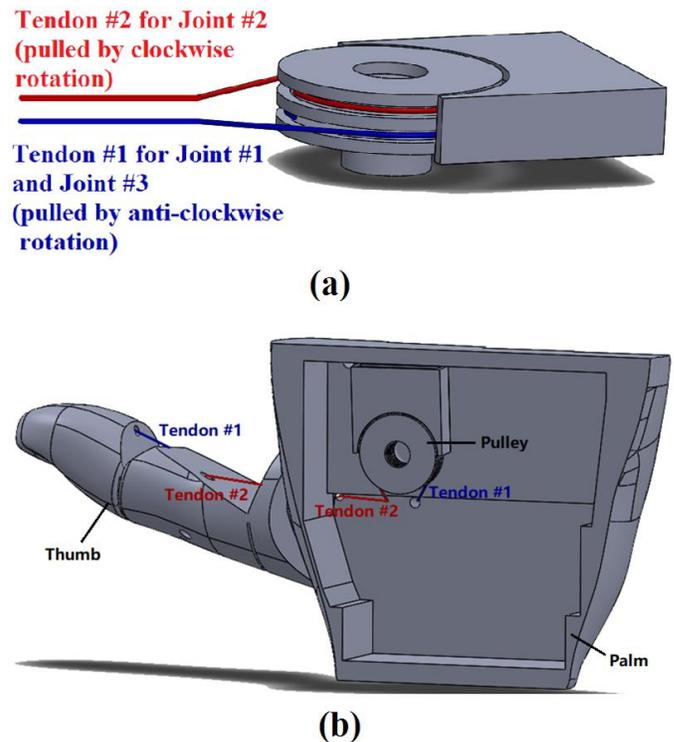


Fig. 3. (a) Concept of modality selection to separately actuate two tendon systems of the robotic thumb (b) the connection of the pulley/motor and the thumb (the tendons' routes inside the structure not shown).

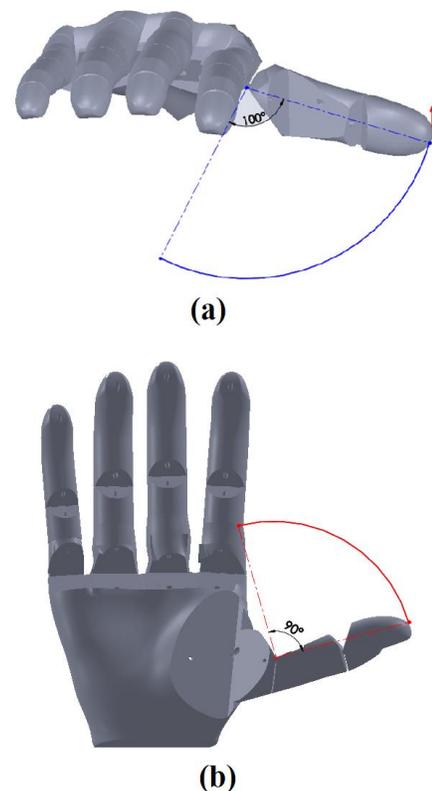


Fig. 4. (a) The trajectory (solid line in blue) of the thumb's tip in Modality 1 pulled by Tendon #1: Abduction/Adduction (b) the trajectory (solid line in red) of the thumb's tip in Modality 2 pulled by Tendon #2: Flexion/Extension.

Fig. 3(b) shows the palm and the thumb viewed from the back (the back cover taken off). The actuator is mounted inside the palm. The connection of the pulley/motor and the thumb is illustrated. Some guiding tubes are used to specify the tendons' routes and reduce friction at the sharp corners.

Though the thumb is controlled by two tendon systems which do not interfere with each other's operation, these two tendon systems cannot operate simultaneously. The workspace of the thumb is restricted to two trajectories corresponding to two modalities, shown in Fig. 4(a) and Fig. 4(b). Though this workspace of the thumb is not as large as that of a thumb controlled by two independent actuators (usually a curve surface), it is sufficient to provide the three commonly used grasps (lateral grasp, power grasp, and precision grasp) identified in Section II.

IV. FABRICATION

A 3D printer (Model: Flashforge Creator Pro) based on fused deposition modeling (FDM) was employed to fabricate the designed structures by extruding commercially available thermoplastic material, including rigid (e.g., ABS, PLA) and soft (e.g., FilaFlex, NinjaFlex) filaments [26].

The hand palm is usually the case to accommodate the actuation system (e.g., motors, pulleys, control boards, etc.). To avoid interference to the actuation components, the palm is better to be least deformable. Therefore, ABS filament, as a rigid material, is employed for the 3D printing of the palm. A rigid palm is also beneficial when to hold/take some relatively heavy weight or strong reaction force.

The variety of a human hand's morphology comes from the deformable nature of the fingers and the thumb, which need to be printed by a soft material. A commercially-available thermoplastic polyurethane, called FilaFlex 82A Original (supplied by Recreus) was used for 3D printing of the flexural hinges, the links for the thumb and the fingers in this work.

The tendons are made of abrasive-resistant braided polyethylene fibers (Manufacturer: SYUTSUJIN, Type: GRAND PE JIGMAN WX8) with the diameter of 0.48 mm and the rated tensile load of 445 N (100 lb). A flexor tendon is pulled by a servo motor (Model: Dynamixel XL-320) together with a tailored pulley (diameter = 16 mm). Due to the intrinsic elasticity, the finger/thumb does not need an extensor tendon to return to its initial state.

V. RESULTS AND DISCUSSION

A. Size and mass

Fig. 5 shows the 3D-printed prosthetic thumb and a real human thumb while Fig. 6 shows the whole 3D-printed UoW/ACES prosthetic hand and a real human hand. From the figures, the size of the thumb and the size of the hand are comparable to those of a regular adult's thumb and hand, respectively. The length of the thumb is 90 mm from the tip to the rotating axis of abduction/adduction. The length of the hand (from the middle finger's tip to the palm's base) is 182 mm while the major width of the palm is 88 mm. In terms of

mass, the thumb itself weighs 23.8 gram while the whole hand (structure only) weighs 124.2 gram. With four electric motors and the electronic parts integrated onboard, the total weight (including two 3.7v 1000mAh batteries) is 261.6 gram, which is much lighter than all of the previously reported prosthetic hands [27]. Its weight is also much lower than that of a real human hand with the comparable size (~400 gram). A prosthetic hand weighing the same as a natural human hand does actually feel heavier than that on an able-bodied person. This is because of the fact that current prosthetic hands are socket based and, therefore, the hand is attached to the limb through a fitted socket. The weight of a prosthetic hand is borne primarily through the skin and tissue, supported by bony landmarks, therefore is much less effective than the natural human body where the weight of the hand is primarily borne by an intact skeletal system. Therefore, it is a good practice to design a prosthetic hand lighter than its biological counterpart. For this prosthetic hand (which we call the UoW/ACES prosthetic hand), the thumb, the index finger and the middle finger are independently controlled by one electric motor, respectively. The ring finger and the little finger are connected and actuated together by using one electric motor.



Fig. 5. The 3D-printed prosthetic thumb and a real human thumb.



Fig. 6. The 3D-printed UoW/ACES prosthetic hand and a real human hand.

B. Grasps and gestures

The most commonly used hand pattern is the power grasp. Fig. 7 shows the power grasps of the soft robotic hand with different shaped and sized objects for daily life. Due to the adoption of underactuation and soft robotics, the prosthetic hand shows good intrinsic mechanical compliance without

requiring any position sensing for position/configuration feedback. The motion control of the hand is realized by adjusting the rotation of the servo motors while the force control is mostly dependent on the intrinsic stiffness of the soft hand. The prototype is strong enough to pick up and hold heavy household objects such as a 600ml water bottle.

The power grasps illustrated in Fig. 7 include both cylindrical (e.g., bottles, drink carton) and spherical (e.g., apple, mandarin, soap) grasps. The thumb is capable of performing both flexion/extension and abduction/adduction with Joint #1 and Joint #3 actuated in series by one tendon. This configuration also provides compliance to the prosthetic hand when conducting spherical power grasps.

When the hand is positioned horizontally and picks up an object, the joints of the fingers and the thumb need to be strong enough to withstand the vertical force due to the object's weight. The design of a flexure hinge with a non-symmetrical notch fulfills this requirement successfully, as shown in the examples of cylindrical power grasps in Fig. 7, and in the accompanying video file demonstrating all grasps and gestures

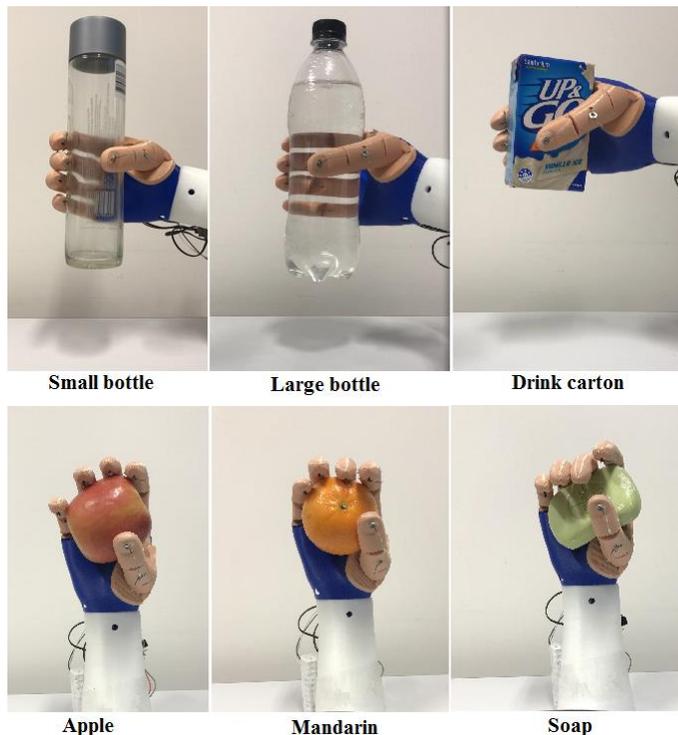


Fig. 7. Power grasps of different objects. Please note that the thumb is in the opposed position for these grasps.

Precision grasp is the second commonly used hand pattern. Fig. 8 shows the pinch of a coin and the pinch of a small ball, respectively, which at least require the flexion of the index finger and adduction of the thumb. The flexion of the thumb works as a supplemental motion and enhances the gripping strength. Fig. 7 also shows the tripod grip of a marker pen, which requires the middle finger to improve the stability of the precision grasp of a relatively long object such as a pen. Similar to the power grasp, the soft robotic hand possesses

good mechanical compliance when performing precision grasp due to its natural softness.

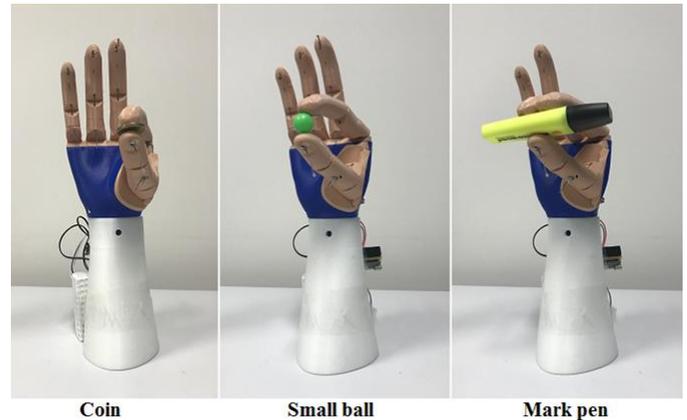


Fig. 8. Precision grasps of different objects.

Another important hand grasp is the lateral grasp, which is successfully achieved by the soft robotic prosthetic hand shown in Fig. 9. By using the method presented in Subsection II.D, the modality of the thumb's motion is switched and the electric motor actuates Joint #2 only instead of Joint #1 and Joint #3. Therefore, the thumb does not conduct any abduction/adduction but flexion only with longer rotational radius (compared to the rotation of Joint #1) so that the thumb can reach the side of the index finger to finish the lateral grasp. This is achieved without increasing the number of actuators, which brings significant benefits to the space consumption and power consumption of the whole prosthetic hand. Moreover, this concept can be employed for the actuation of the other four fingers to either increase the versatility of finger movements or reduce the total number of electric motors used.

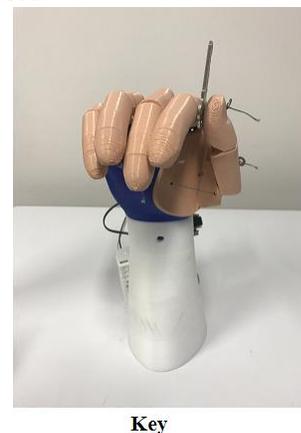


Fig. 9. Lateral grasp of a key. Please note that the thumb is in the non-opposed position for this grasp.

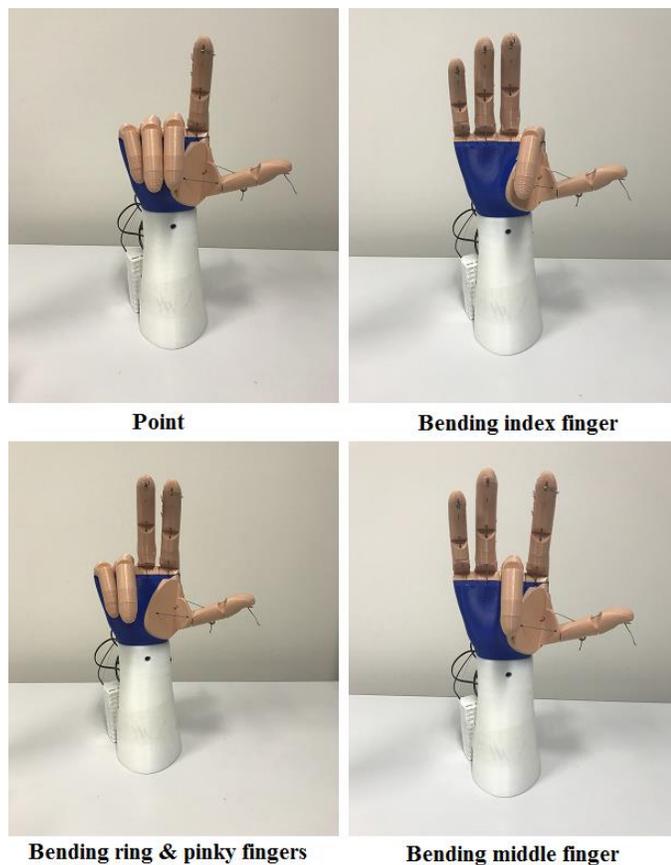


Fig. 10. Part of other gestures by the soft robotic prosthetic hand.

The soft robotic hand is also capable of some hand patterns for postural purpose, including pointing, bending index finger, bending ring and pinky fingers, and bending middle finger, shown in Fig. 10. The thumb can be at either opposed position or non-opposed position for these postures.

C. Force and speed

The major factors that affect the tip force of the thumb and its moving speed are the electric motor's specifications, the pulley's size, the stiffness of the flexure hinge, and the frictional resistance to the tendon. The tip force of the thumb was measured by pressing the thumb onto a 6-axis force sensor (Manufacturer: ME-Meßsysteme, Model: K6D27). With the servo motor (Model: Dynamixel XL-320) and an 18-mm-diameter pulley, the maximum tip force of the thumb reaches approximately 2 N. From the recorded movements by a camera, it is found that the proposed robotic thumb can finish the full adduction in 400 ms while it takes ~ 300 ms to complete the full flexion for the lateral grasp due to the shorter stroke. The soft robotic thumb relies on the intrinsic elasticity of the flexure hinges to conduct abduction and extension. It takes 360 ms for the soft thumb to return from the full adduction to the full abduction while the extension recovered from the full flexion only takes 240 ms. The speed is within the acceptable range (1 second), for a robotic prosthetic hand [4].

One limitation of the proposed actuation system is associated with the response time due to the transition between

two modes of operation of the thumb. When the motor rotates in one direction, one tendon is pulled and the other tendon gets loose. As the mode of operation is changed, it needs some time for the loose tendon to recover its tension. For a prosthetic hand with indirect transition between the lateral grasp and the other grasps, the thumb always needs to return to its original position and perform the next grasp. Therefore, this issue does not affect this kind of prosthetic hand. However, for a prosthetic hand requiring more intuitive control, the direct transition between the lateral grasp and the other grasps is desired. In that case, the total response time will be the sum of the time for recovering from the current grasp and the time for reaching the next grasp. For our hand prototype, this time is approximately 640 \sim 660 ms, which is still within the acceptable range (1 second) for a robotic prosthetic hand.

Though the hand prototype presented in this work is capable of grasping some household objects (as shown in Fig. 7), its thumb's force needs to be further enhanced in order to handle heavier objects. Both the force and the moving speed of the thumb will be improved by employing stronger motors and optimizing the tendon's routes for less friction in the future work.

D. Mechanical life cycle of the joint

The mechanical life cycle of the joint was measured by using the experimental setup shown in Fig. 11. After 1.5 million cycles of bending and releasing, the joint with the flexure hinge did not show any sign of fatigue or structural failure, which indicates its sufficient strength for a prosthetic hand's thumb or finger(s).

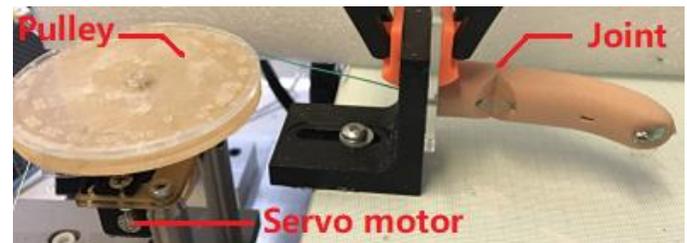


Fig. 11. The experimental setup to test the mechanical life cycle of the joint with the flexure hinge.

VI. CONCLUSIONS AND FUTURE WORK

In this work, we propose a novel design of a monolithic soft robotic thumb for an anthropomorphic prosthetic hand. The structures of the thumb and the whole prosthetic hand were fabricated using FDM additive manufacturing. Both of them have dimensions or sizes similar to the human's but much lower weights. Flexure hinges with nonsymmetrical V-shaped notches provide the joints with an improved grasping stability when tangential force is exerted on the thumb/finger. A two-axis flexure hinge connected in series enables the thumb to conduct both palmar abduction/adduction and flexion/extension with one-tendon actuation. By using the concepts of soft robotics and underactuation, the thumb shows sufficient mechanical compliance and performs well in power

grasps (cylindrical and spherical ones), precision grasps (pinch and tripod grip) and lateral grasps with different shaped and sized objects. Another feature of our design is the innovative and compact mechanism allowing the thumb to conduct abduction/adduction and flexion/extension in parallel by using ‘only one actuator’—pushing the limits for underactuation. With this capability of modality selection, the soft robotic thumb keeps its grasping versatility compared to those using two actuators while the reduced number of actuators saves the space and the power consumption, which are significant to develop a practical, low weight and low cost robotic prosthetic hand.

The future work aims to provide the soft robotic hand, the UoW/ACES prosthetic hand, with stronger grasping strength. To achieve this, more powerful electric motors with higher torque and higher speed (i.e. power) will be tested and equipped for the thumb and the other fingers. Meanwhile, the tendon routes will be optimized to reduce the frictional resistance. The stiffness of the flexure hinges will also be optimized to lower the resistance without sacrificing the ability of using intrinsic elasticity to recover the movements of the thumb/fingers.

The current prosthetic hand for which the thumb is designed in this work is based on direct myoelectric control. The muscle activity in the forearm is detected by the electromyography (EMG) electrodes. A pattern recognition algorithm is used to classify the EMG signals into two groups. One group of the EMG signals is used to trigger the actuation of the set hand gesture/grasps while the other group of EMG signals is used to change the set hand gesture/grasp to another set. For the future hand prototypes, the pattern recognition technique will be improved to identify more groups of the EMG signals so that each group can be designated to one certain hand gesture/grasp. In this way, a prosthetic hand with more intuitive control can be achieved.

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