A 3D Printed Soft Robotic Hand With Embedded Soft Sensors for Direct Transition Between Hand Gestures and Improved Grasping Quality and Diversity

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***Abstract*—In this study, a three-dimensional (3D) printed soft robotic hand with embedded soft sensors, intended for prosthetic applications is designed and developed to efficiently operate with new-generation myoelectric control systems, e.g., pattern recognition control and simultaneous proportional control. The mechanical structure of the whole hand ('ACES-V2') is fabricated as a monolithic structure using a low-cost and open-source 3D printer. It minimizes the post-processing required for the addition of the embedded sensors in the hand. These are significant benefits for the robotic hand that features low cost, low weight (313 grams), and anthropomorphic appearance. With the soft position sensors added to the fingers, the fingers' positions can be monitored to avoid self-collision of the hand. Besides, it allows a robotic prosthetic hand to eliminate the conventional way of returning to the neutral full open position when switching from one type of gesture to another. This makes the transition between the hand gestures much faster, more efficient, and more intuitive as well. Further, initial contact detection of each finger is achieved for the preshaping of multi-finger grasps, e.g., tripod grip and power grasps, to improve the stability and quality of the grasps. Combinations of different gestures allow the hand to perform multi-stage grasps to seize and carry multiple objects simultaneously. It can potentially augment the hand's dexterity and grasping diversity. Providing direct transition between the hand gestures and improved grasping quality and diversity are the primary contributions of this study.**

***Index Terms*—Soft robotics, prosthetic hand, soft sensors, finger position tracking, direct gesture transition, preshaping, multi-stage grasps.**

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I. Introduction

TREMENDOUS efforts have been directed towards the restoration of upper limb function for people who suffer from upper limb loss. As an artificial part of the human body, a prosthetic hand is desired to match its biological counterpart in many respects, including cosmetic, postural, and grasping functions. A self-contained (i.e., actuators placed inside the hand) anthropomorphic robotic hand is considered as one of the best candidates. Thanks to the rapid advancements in robotics technology, robotic prosthetic hands have evolved from a tool equipped with one electric motor, capable of only one degree of freedom (DOF) movement (i.e., opening and closing), to a powerful bionic device with diverse grasping capabilities by using multiple mini-sized electric motors [1]. Such a robotic hand is generally controlled by a user via surface electromyogram (sEMG) electrodes measuring the myoelectric activities of the residual arm's muscles, the so-called myoelectric hand.

For commercial myoelectric hands, direct control or 2-myosites sequential control is widely used as a user-hand interface in clinical settings. One major limitation of this control interface is that a user cannot directly control the hand to get to a desired gesture before this gesture is switched 'active'. The switching between different gestures is usually achieved manually or using muscle co-contraction of two myo-sites. To reduce its cost and weight as much as possible, a robotic prosthetic hand is generally designed to match the capability of the user-hand interface. With direct control, as only one gesture is active at one time, all the hand movements of each gesture are pre-programmed. To perform a different gesture, the hand returns from the previous gesture to a neutral position which is usually a fully opened position. In presence of the neutral position, the hand moves from a known starting position to a pre-set targeted position for a specific gesture so that the trajectories can be pre-determined. No position feedback is required and almost all the commercial hands are based on open-loop control without position sensors onboard.

This scheme works effectively and economically with direct control.

The emergence of pattern recognition (PR) based user-hand interfaces is making the change to improve the intuitiveness of myoelectric control [2]–[5]. Different from direct control, PR control uses machine learning algorithms to detect a user's varied upper limb intentions so that each gesture can be directly commanded through different muscle contractions. No manual switching is required to make a gesture 'active'. In other words, all the pre-selected gestures are 'active' and the hand needs to be ready to perform any gesture whenever the user intends to. Two commercial PR systems, Coapt Gen2 (Coapt) and Myo Plus (Ottobock) have recently been applied to clinical use [6], [7].

With PR control, a robotic prosthetic hand is expected to perform gesture transitions more intuitively and perhaps more frequently as the cumbersome manual switching is eliminated. If the hand is required to return to its neutral position to start a different gesture every time, the operation appears particularly non-intuitive and inefficient. As PR control can provide multi-DOF commands, the hand is expected to perform gesture transitions seamlessly regardless of the position of the hand. When the neutral position is eliminated to achieve a seamless transition, the robotic hand starts to move from an unknown position, making the pre-programmed movements risky because the hand digits will move blindly without real-time position tracking. Self-collision may happen, which can cause the hand's malfunction or even permanent damage. As a hand grasp is essentially a cooperative action of all the hand digits, it is difficult to achieve a high-quality grasp without knowing each digit's position when pre-programmed movements are not available anymore. Therefore, for seamless transitions between gestures, there is a need to upgrade existing robotic prosthetic hands.

Recently, there has been an increasing interest to employ soft robotic hands for prosthetic purposes due to their promising features, i.e., low capital and maintenance costs, lightweight, and good mechanical compliance addressing safety concerns [8]–[14]. In this study, a novel soft robotic hand intended for prosthetic purposes is proposed and developed with enhanced control and grasping performance compared with the existing commercial hands. This hand is three-dimensional (3D) printed monolithically with embedded soft position and touch sensors for each of its four fingers and thumb. Real-time tracking of each joint is realized so that the hand's movement can be precisely controlled to perform different gestures with seamless transition directly between any two of them.

This study is a significant step to implement intuitive gesture transition and enhance grasp quality for a soft robotic hand for prosthetic purposes. In this way, the hand's maneuverability can catch up with the capabilities of the revolutionary PR based user-hand interfaces, which paves the way towards bringing the operation of hand prostheses one step closer to their natural counterparts.

II. Objectives

A user-hand interface that allows the control of individual fingers is ideal for prosthetic hand users. However, there is no indication that any myography-based (i.e., either non-invasive or invasive) interface can achieve this goal in the short term. As a practical approach with current technology, a PR system detects and outputs the user's intention as different hand gestures, which are the synergies of all the fingers and thumb. Therefore, the very first objective for any robotic prosthetic hand is to determine the desired grasps and gestures.

To achieve an intuitive transition between any two grasps, the hand needs to be able to start the requested grasp from the PR system straightaway without returning to its neutral position. Therefore, the second objective of this work is to provide the hand with the capability of online position tracking of all the joints and motion planning based on the acquired position information. This can make sure self-collision of the hand is avoided and the switching of gestures/grasps is smooth and seamless.

Another main objective is to improve grasp quality by enabling the hand to perform form closure when grasping an object, which is realized by preshaping the hand to envelop the object geometrically. Through the detection of each finger's initial contact with the object, an external wrench (i.e., force and moment) can be achieved to avoid the object's movement before being grasped securely. This can greatly improve the stability of the power grasp for a robotic prosthetic hand, especially when four fingers cannot reach the object at the same time. This situation is often encountered with a hand with a PR system since its power grasp does not necessarily start from its fully opened position anymore.

Some common benefits of soft robots are also targeted for this hand, including fabrication by 3D printing for easy customization, and realization of a lightweight and affordable (i.e., low-cost) robotic prosthetic hand.

III. Materials and Methods

A. Design, Modeling, and Fabrication

The computer-aided design (CAD) model of the soft robotic hand ('ACES-V2') is shown in Fig. 1. The 'ACES-V2' hand has an anthropomorphic appearance as this is one of the key factors for the acceptance of prosthetic hands [15], [16]. Four fingers are designed based on our previous work, which reported on a 3D printed soft robotic finger with embedded bending and touch sensors for closed-loop position and force control [17], [18]. Two joints in the form of 1-DOF flexure hinges are employed for each finger in which one pneumatic bending sensing chamber is embedded in each. The rotational displacement of each joint can be detected from the pressure change in the bending chamber. For simplicity, the thumb is also designed to have two 1-DOF joints only. The lower joint enables the thumb's palmar abduction/adduction while the upper joint supports its flexion/extension. Similar to the fingers, pneumatic bending sensing chambers are integrated for detecting the thumb's position. Also, a pneumatic chamber is embedded inside the fingertip of each of the four fingers and the thumb as a force sensing chamber. These touch sensors can also be potentially used for tactile sensory feedback. More details about the touch sensors can be found in our previous work [17]. It is important to note that the intrinsic elasticity of the joints is responsible for the fingers' extension.

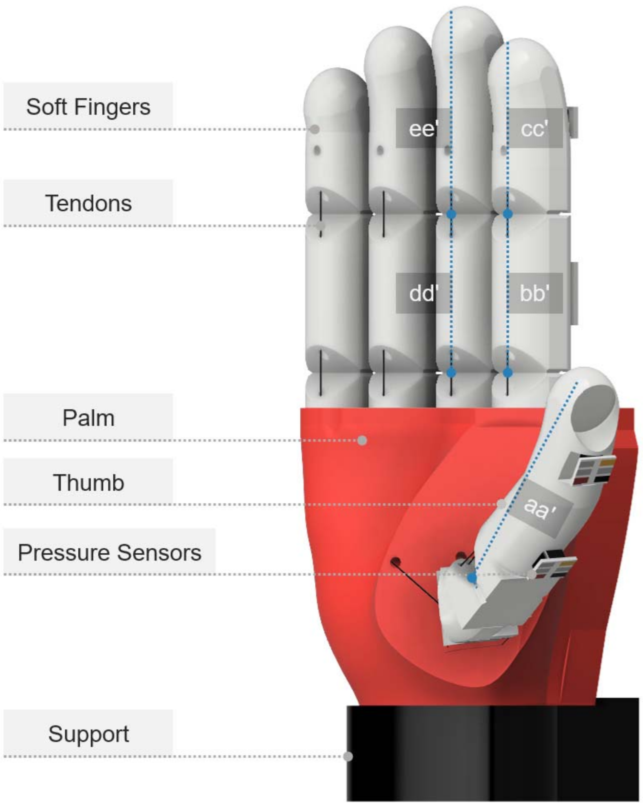

Fig. 1. ACES-V2 soft robotic prosthetic hand computer-aided design (CAD) model.

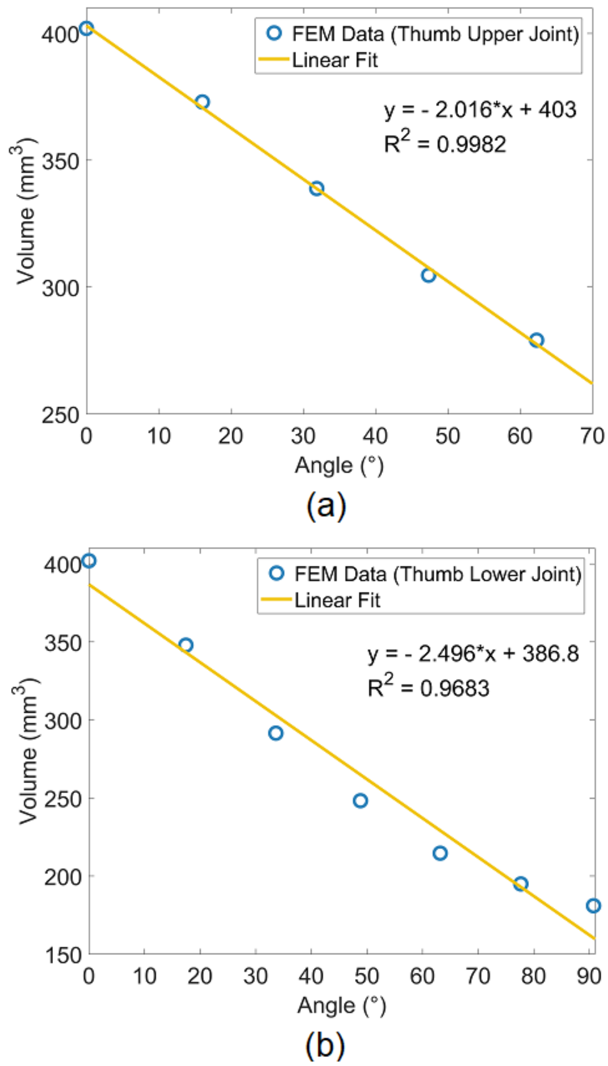

Fig. 2. FEM results showing the relationship between the bending angle and the internal volume for (a) the upper joint and (b) the lower joint of the thumb, respectively.

The 'ACES-V2' hand is modeled in Autodesk Fusion 360 (Autodesk Inc.). The thumb which is newly designed in this study is simulated using finite element modeling (FEM) to find the relationship between the bending angle and the internal volume for each of its pneumatic chamber (i.e., upper and lower joints). The FEM results show the relationship between the bending angle and a chamber's internal pressure since $PV = \text{Constant}$ with the assumption of no temperature change according to the ideal gas law (P: Pressure, V: Volume) [17]. For ease of calibration and mapping the bending angle to the pressure change, a linear relationship is desired. The topologies of the thumb's two joints are optimized to achieve linearity and to minimize the bending stiffness as well. The joints' models are meshed using higher-order tetrahedral elements. The FEM results, shown in Fig. 2, indicate that a linear relationship exists between the bending angle of the internal volume for the upper and lower joints of the thumb, respectively.

The optimized CAD model of the hand is sliced using a commercial software (Simplifiy3D, LLC, OH) where the 3D printing parameters were optimized to obtain airtight soft chambers (i.e., position and touch chambers) and soft fingers with high quality exteriors [19]–[21]. The soft monolithic fingers and thumb are 3D printed using a commercially available thermoplastic polyurethane (TPU) known as NinjaFlex (NinjaTek, USA) while the palm is 3D printed using acrylonitrile butadiene styrene (ABS) due to the desired structure stability and minimum deformation caused by some internal or external loads. The pressure in each pneumatic chamber is measured by a solid air pressure sensor (ABPDANT015PGAA5, 0–15psi Gauge, 0.25% Accuracy, Honeywell International Inc.). A microcontroller board (Arduino Mega 2560, Arduino) is used to acquire all the pressure measurements and send them to a computer for processing.

The hand is self-contained with all the actuators in it with a total mass of 313 grams. For the sake of being lightweight and simple, tendon-driven underactuation is employed for all the fingers and the thumb to enhance the mechanical compliance of grasps. All the tendons are made of abrasive-resistant braided polyethylene fibers with a diameter of 0.48 mm and a rated tensile load of 445 N (Manufacturer: SYUTSUJIN, Type: GRAND PE JIGMAN WX8).

Full actuation is employed for the thumb since it is critical to the hand's grasping and dexterity as it is responsible for up to 40% of a hand grasps [22]. Initially, five tendon-driven mechanisms were designed, two for the thumb, one for the index finger, one for the middle finger, and one for the ring and little fingers together. The motor for the flexion/extension of

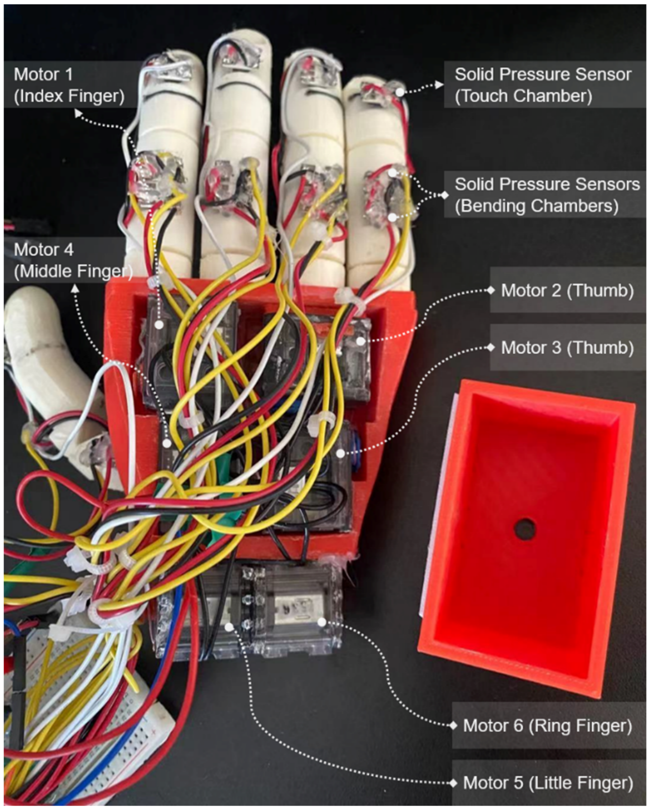

Fig. 3. Back view of the 'ACES-V2' robotic hand. This view shows the location and configuration of the solid pressure sensors and servo motors.

the thumb was initially designed to sit inside the thumb's phalange to save space inside the palm, which was a usual strategy in robotic hand design [1], [23]. The other four motors were designed to be housed inside the palm. Ideally, DC motors with small strong pulleys (i.e., 2.5 mm in diameter in [24]) can provide better performance in terms of pulling strength and speed. However, it usually requires a more complicated control circuit. As the main aim of this work is to develop and test the concept of seamless transition between gestures, simple hardware is employed for the sake of rapid prototyping. Servo motors (Dynamixel XL-320) with 3D-printed plastic pulleys (10 mm in diameter) are used. Since the relatively large pulleys are used and the torque output is constant, the pulling force from each motor is weakened. Therefore, the number of motors is increased from five to six motors so that each finger can be pulled by an individual motor. Besides, as the servo motors used are not cylindrical, they cannot be placed inside the thumb's phalange. Therefore, the initial design is altered and the final motor configuration is shown in Fig. 3. An open-source motor controller (OpenCM9.04) is employed to provide communication between the computer and the motors.

The total length of the fabricated prototype is 203 mm, which can be potentially reduced to 179 mm (i.e., from the middle finger's tip to the palm's base) if the motor-pulley system is optimized by using good-quality DC motors (e.g., Faulhaber 1024M006SR+10/1 64:1) and smaller pulleys (e.g., machined stainless steel) as well as a corresponding advanced control circuit. The major width of the palm is 92 mm. The hand's total mass is 313 grams, including the mass of the mechanical structure, six electric motors, and fifteen solid pressure sensors. This hand is much lighter compared to the commercial myoelectric hands (i.e., typically over 500 grams). The details of the design and fabrication can be found in our previous work [25].

B. Targeted Hand Grasps/Gestures

Three hand grasps, including power grasp, pinch grip (i.e., index finger and thumb), and lateral grasp (i.e., key grip) are usually identified as the most useful hand grasps [26], [27]. They are all enabled for the 'ACES-V2' hand. Tripod grip is also selected as a popular supplementary precision grasp for pinch grip. Index pointing is included for clicking purposes and postural use. Thumb-up is selected as the releasing-type gesture corresponding to lateral grasp (i.e., key grip). Besides, it can be used as a hook for lifting and it is a common gesture as well. Lastly, the hand gesture of the full opening is a must as it can release all the other hand grasps/gestures. It can also work as a 'platform' gesture with all fingers fully extended and the hand's front facing upwards to support an object. Overall, seven commonly used hand grasps/gestures are selected for people's activities of daily living (ADL), listed below:

- hand fully opening
- hand fully closing (i.e., power grasp)
- pinch grip with index finger and thumb
- tripod grip with index and middle fingers, and thumb
- lateral (i.e., key) grip
- index pointing
- thumb-up/hook

C. Determining Final Positions of All the Hand Digits for Each Hand Gesture

Each hand gesture has special features that differentiates it from other gestures. For fully opening, fully closing (i.e., power grasp), and thumb-up, the final positions of the hand digits are unanimous. However, for the other hand gestures, there is flexibility in this regard. As long as its key feature are made, the requested hand gesture is considered to be achieved (i.e., successful gesture). For example, the key feature of pinch grip is the thumb touching the index finger while the other three fingers' positions are usually not important. A similar situation occurs to tripod grip, in which the ring and little fingers' positions do not affect people's perception of whether tripod grip is formed or not. The final positions of the hand digits are determined for each hand gesture, as shown in Table I. In Table I, a cell is left blank if a digit's movement is considered unnecessary for a corresponding hand gesture, in which all the unnecessary movements are removed for the sake of power and energy saving.

D. Direct Transition Between Hand Grasps

To realize a direct and seamless transition between hand grasps, the neutral position must be eliminated. The key is to provide the hand with online position tracking capability using the embedded soft sensors. Based such online position information, a motion control system can calculate the optimized trajectories for all the hand digits so that the transition can be conducted smoothly and efficiently without self-collision.

TABLE I
FINAL POSITIONS OF HAND DIGITS FOR THE TARGETED HAND GESTURES

	Index	Middle	Ring	Little	Thumb
Fully opening	E	E	E	E	E
Fully closing (Power grasp)	F	F	F	F	F, O
Pinch grip	F				F, O
Tripod grip	F	F			F, O
Lateral grip	F				F, NO
Index pointing	E	F	F	F	
Thumb up	F	F	F	F	E, NO

*E: Fully Extended, F: Fully Flexed, O: Opposed to Fingers with Full Abduction, NO: Non-Opposed to Fingers with Full Adduction, Blank Cell: No Movementfull. The key feature of the index pointing is that the index finger is fully extended and the other three fingers are flexed. Therefore, we assume that the thumb can remain in its position.

The avoidance of self-collision is achieved through three main steps. In Step 1, four fingers are designed to bend/extend within the parallel planes so that they never collide with each other in space. The range of motion (ROM) for the thumb's abduction is limited so that the thumb can only reach the middle finger for the tripod grip. In this way, the risk of self-collision can be reduced, which is likely to happen to the thumb and the index/middle finger only. For Step 2, some rules are set, namely:

(i) When abduction/adduction and flexion are both involved for the thumb, the former is set to move before the latter.

(ii) When abduction/adduction and extension are both involved for the thumb, the latter is set to move before the former.

(iii) When the thumb is at the non-opposed position and only flexion is involved (i.e., key grip), the thumb is set to stop at 50% flexion and wait until the finger(s) at the final targeted position(s) and then go for its full flexion.

(iv) When the thumb is within the index or middle finger's plane of movement (POM), the fingers are set not start to move until the thumb reaches its final position.

Based on Step 1 and Step 2, self-collision should not take place in a normal operation. However, in case an abnormal operation happens (i.e., motor failure), a fail-safe procedure is designed as Step 3 to detect self-collision as fast as possible so that damages can be minimized. Once self-collision is detected, the hand is set to a full stop, and only a fully opening position can be performed. To activate this fail-safe procedure, two conditions need to be met at the same time:

- The thumb's tip is within the POM of the index/middle finger. The position of the thumb's tip is monitored online by using forward kinematics.
- As shown in Fig. 1, the distal phalange of the thumb is defined as one line-segment (aa') while the two phalanges of the index finger and two phalanges of the middle finger are defined as four line-segments, respectively. The closest distance between aa' and each of the other four line-segments is calculated online. If it is below a certain value (i.e., based on the diameters of the hand digits), the thumb is considered to collide with the index/middle finger.

When the hand is not at risk of self-collision, all the digits are designed to move simultaneously as much as possible, which saves time to form the desired hand gesture and allow the robotic hand to behave more like a biological one.

E. Preshaping of the Hand for Improved Quality of Grasps

It is essential for a stable grasp to have more contact points (i.e., area) evenly distributed on the surface of a grasped object. These contact points can improve the balancing of the forces applied on the object by the fingers and the thumb. As the hand does not start from a fully opening position for a grasp, the time required by each finger to make contact with the object varies when performing multi-finger grasps, which leads to the reduction in the number of contact points when the hand starts to firmly grip the object. This may cause a force imbalance on the object and consequently lead to an unstable grasp (i.e., failed grasp). Even when a power grasp is performed by starting from the hand fully opening position, this situation might also arises when grasping an object with a non-uniform perimeter or irregular outer geometry (i.e., shape). To alleviate this problem, preshaping the hand is implemented to allow all the fingers to touch the object first and envelop it geometrically before large forces are applied in order to grasp the object securely. Detecting the initial contact for each finger is a significant step for preshaping a grasp that requires multiple fingers, e.g., tripod grip or power grasp. In the literature, fingertip sensors or motor current sensing are usually used for initial contact detection. However, the former does not work if the proximal phalange of a finger rather than its tip makes contact with the object first. For the latter, such sensing method is still not accurate and reliable. In this work a practical approach is employed which considers that the finger gets in touch with an object once any of its two joints stop rotating or bending.

F. Multi-Stage Grasps

As the direct transition between grasps is available, the hand does not have to release a grasp before performing another one. Instead, different grasps can be combined to provide users with multi-stage grasps to hold more than one object at the same time, which is a feature of a biological hand. For example, the hand can perform a pinch grip to hold a small-sized object such as a coin and then perform a power grasp, by which the other remaining three fingers bend to hold a second object against the palm. Another example is that the hand can perform a thumb-up/hook to hold a cylindrical object first and then perform a key grip to hold a second object such as a key. Users can create different combinations of grasps depending on their needs. Multi-stage grasps can potentially improve the flexibility and dexterity of the hand grasps, making the robotic hand's operation one step closer to their biological counterparts.

There are no fixed operation steps or operation routines to combine different grasps. Once the users are trained to be skilled in PR control, they are expected to confidently activate any gesture from their own pre-selected list of gestures whenever they want. Then, the users may find some commonly used combinations of gestures, or multi-stage grasps, to suit

TABLE II
ELAPSED TIME (UNIT: SECOND) FROM THE FINAL POSITION OF ONE HAND GESTURE TO THE FINAL POSITION OF ANOTHER

	Fully Open	Fully Closed	Index Point	Thumb-up	Key	Pinch	Tripod
Fully Open		1.38 ± 0.08	0.96 ± 0.04	1.13 ± 0.04	1.07 ± 0.03	0.95 ± 0.05	1.17 ± 0.03
Fully Closed	0.97 ± 0.06		0.63 ± 0.03	1.00 ± 0.04	1.13 ± 0.03	0.94 ± 0.04	1.00 ± 0.03
Index Point	1.11 ± 0.06	1.10 ± 0.03		1.17 ± 0.04	1.24 ± 0.05	1.01 ± 0.05	1.28 ± 0.03
Thumb-up	1.02 ± 0.03	0.91 ± 0.03	1.14 ± 0.04		0.5 ± 0.03	0.9 ± 0.05	1.04 ± 0.05
Key	0.93 ± 0.03	1.44 ± 0.05	1.14 ± 0.05	1.02 ± 0.03		0.77 ± 0.03	1.10 ± 0.04
Pinch	0.93 ± 0.03	1.03 ± 0.03	0.92 ± 0.03	1.06 ± 0.05	0.74 ± 0.04		0.94 ± 0.04
Tripod	0.93 ± 0.06	0.94 ± 0.04	0.70 ± 0.04	1.44 ± 0.05	0.85 ± 0.05	0.53 ± 0.04	

their own needs in life. Subject to different needs, the multi-stage grasps can be quite individual to each user. Since they are commonly used, the users get to operate or practice their own multi-stage grasps frequently, helping to improve the proficiency.

IV. Testing and Performance of 'ACES-V2' Hand

A. Diverse Grasps and Gestures

Fig. 4 shows the ACES-V2 hand performing some of the most used daily-life hand gestures, including cylindrical power grasp, spherical power grasp, thumb-up, lateral/key grip, pinch, tripod grip, and index pointing. Due to the adoption of soft robotic technology and underactuation, the soft robotic hand showed good inherent mechanical compliance, allowing it to adapt itself to the grasped objects' profiles.

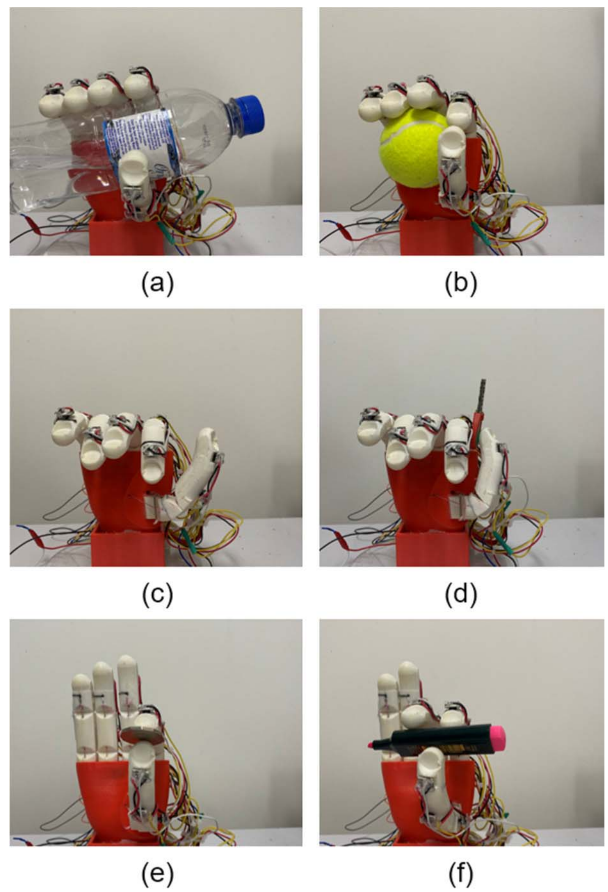

Fig. 4. Grasps/gestures by the 'ACES-V2' soft robotic hand. (a) Power grasp of a water bottle. (b) Power grasp of a tennis ball. (c) Thumb-up. (d) Key grip. (e) Pinch grip of a coin. (f) Tripod grip of a marker.

B. Direct Transition Between Hand Gestures

Self-collision usually happens during the transition stage only. To verify that self-collision is avoided, the 'ACES-V2' hand was tested by performing all the combinations of successive transitions. No self-collision was observed among all transitions.

As noted before self-collision can happen in an abnormal operation such as motor failure. To assess this scenario, both the index and middle fingers were manually stopped to mimic their failure. If either of them intersected the trajectory of the thumb's movement, the fail-safe procedure would be activated to stop the thumb and wait for the hand to return to its fully open position. This test was repeated multiple times in which no collision was observed. Similarly, when the thumb was manually stopped to intersect the trajectory of the movement of the index or middle finger, the fail-safe procedure was observed to stop the fingers to prevent self-collision.

Table II shows the elapsed time for the hand to move from the final position of one gesture (left column) to the final position of another newly performed gesture (top row). The tendons' pulling and releasing phases were smooth, and the joints' flexion and extension were instantaneous with no observable delay. Therefore, with the pre-set final position for each hand gesture, the measurements of the elapsed time are repeatable with minor standard deviations as shown in Table II.

The time for opening-hand or closing-hand between 0.8 s and 1.5 s is considered adequate for prosthetic hands to conduct ADLs [1]. Table II shows that this time range was achieved using our implemented approach. Compared with a prosthetic hand with a neutral position inclusion between different gestures a direct transition from one hand gesture to another without the necessity to return to a neutral position can save almost half the time on average.

C. Preshaping of Multi-Finger Grasps

The tripod grip and power grasp were selected as multi-finger grasps to test the preshaping performance of the hand. As discussed, the initial contact is critical for the hand to achieve preshaping of a grasped object. It is shown in

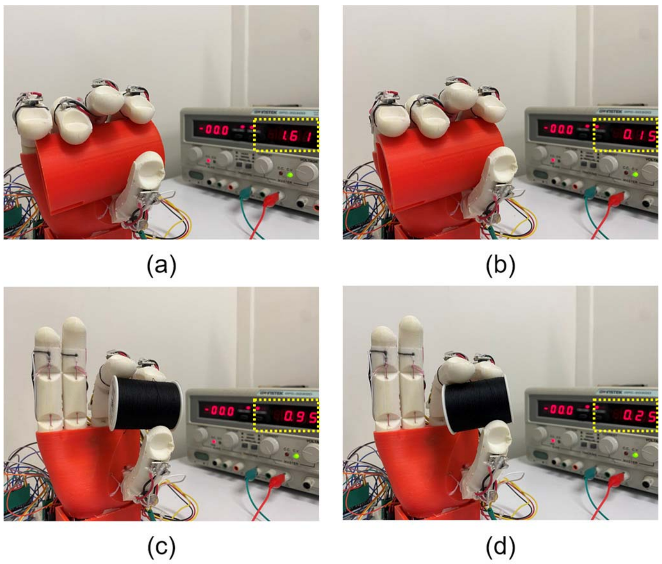

Fig. 5. (a) Power grasp of a cylinder without initial contact detection, and (b) with initial contact detection. (c) Tripod grip of a spool without initial contact detection, and (d) with initial contact detection. The electric current measurements are highlighted using yellow dotted rectangles.

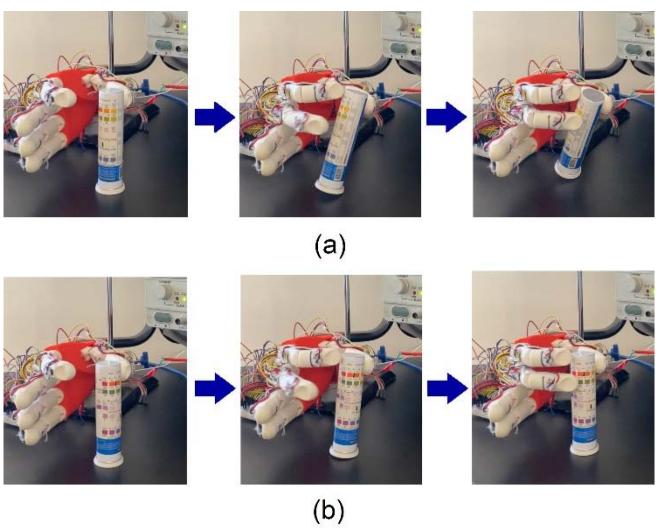

Fig. 6. (a) Tripod grip of a cylindrical object without preshaping. (b) Tripod grip with preshaping.

Fig. 5 that the initial contact of each finger was successfully detected when the tripod or power grasp was conducted. If no initial contact detection was applied, the fingers would continue to bend after touching the object and consequently lead the motors to draw a high electric current from the power source, as shown in Fig. 5(a) and 5(c). With the initial contact detection, all the fingers stopped bending immediately after getting in contact with the object which led the motors to draw a much lower electric current, as shown in Fig. 5(b) and (d).

Additional tests were conducted to show the improved grasp quality of the tripod grip and power grasp by comparing the cases in which preshaping is excluded and included respectively (Video S1). Fig. 6(a) shows the progress of the tripod grip of a cylindrical object without preshaping (first part of Video S1). As shown in Fig. 6(a), the index finger made contact with the object earlier than the middle finger since the two fingers started moving from different positions. When the index finger touched the object first, it kept applying a force on it. Without the support from the middle finger (i.e., not arriving yet), the object got tilted. Upon the arrival of the middle finger the tripod grip was already formed and the object was already unbalanced which resulted in an unstable grasp. In Fig. 6(b), the tripod grip was performed on the same object but with the inclusion of preshaping (second part of Video S1). Due to the detection of initial contact, the index finger did not apply an additional force onto the object when it first touched it. Instead, the index finger remained in place until the middle finger reached the object as well. As observed the force imbalance issue was alleviated which drastically improved the grasp quality (second part of Video S1). The grip force from both the fingers and the thumb was applied onto the object only when the form closure was achieved through preshaping which improved the stability of the tripod grip. The tripod grip was tested again with a different object that has a different shape (a highlighter pen with a rectangular shape). The third part of Video S1 shows the progress of the grip without the inclusion of preshaping, in which the tripod grip failed due to a force imbalance. However, as shown in the fourth part of Video S1, the force imbalance was eradicated through the inclusion of preshaping, leading to a successful grip.

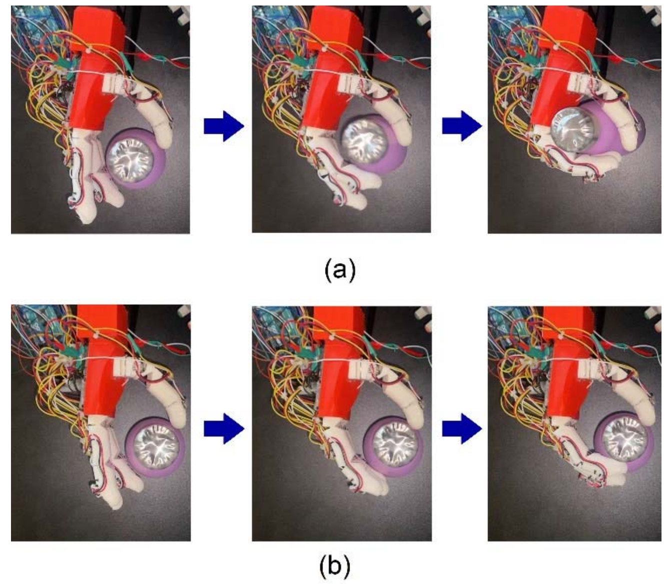

Fig. 7. (a) Power grasp of a water bottle without preshaping, and (b) with preshaping.

The power grasp was tested with a cylindrical water bottle with a non-uniform-diameter (i.e., a gradually increasing from the middle to the top of the bottle). Fig. 7 shows the top views of the progress of the power grasps. In Fig. 7(a), the ring and little fingers touched the bottle first and kept pushing against it before the remaining fingers reached the bottle which led to the tilting of the bottle tilt and consequently achieving an unstable power grasp. This behavior can be observed in part five of Video S1. The grasp instability was improved by through the inclusion of preshaping, as shown in Fig. 7(b) and the part

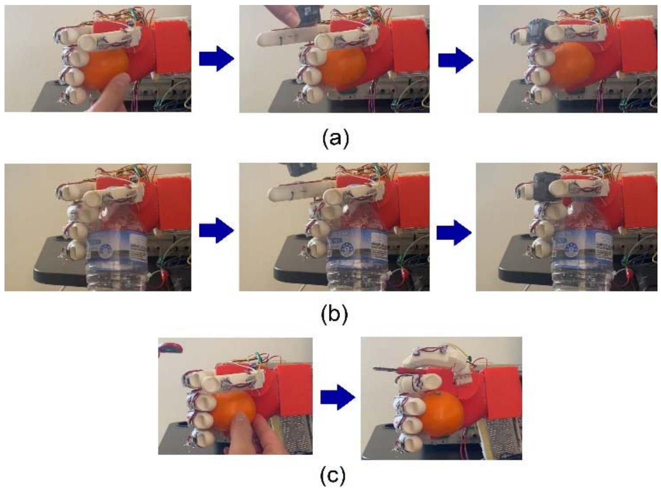

Fig. 8. Multi-stage grasps: (a) spherical power grasp + index pointing + pinch. (b) Cylindrical power grasp + index pointing + pinch. (c) Spherical power grasp + key grip.

six of Video S1. It is observed that the bottle barely moved when all the fingers reached the bottle to achieve a firm and stable power grasp. The exclusion and inclusion of preshaping were also considered to compare the power grasps with other objects having different shapes (i.e., cylinder, elliptical cylinder) in which the preshaping successfully alleviated the force imbalance issue that was also dependent on the weight of the objects and the time difference between the arrivals of the fingers to the target object. It is important to note that if it comes to a lighter object or a delicate power grasp is desired (i.e., holding a fragile object), the need of preshaping inclusion can be much more obvious.

D. Testing the Multi-Stage Grasps

Several tests were conducted to validate the feasibility of multi-stage grasps (Video S2). As shown in Fig. 8(a) and in part one of Video S2, a spherical power grasp was performed first to grab an orange. Then the index pointing gesture was performed by releasing the index finger and the thumb and keeping the remaining fingers in their position to keep holding the orange. Afterwards, the hand performed a pinch grip to grasp a second object. Similarly as shown in Fig. 8(b) and in part 2 of Video S2a cylindrical power grasp was performed first to hold a water bottle. Then, the index pointing and pinch grip were conducted sequentially so that the hand successfully held the second object. Likewise, as illustrated in Fig. 8(c) and in part 3 of Video S2, the hand performed a power grasp to seize a mandarin first and then performed a key/lateral grip to grab a key, enabling the hand to carry two objects simultaneously.

V. Discussion

A. Preshaping

Overall, the inclusion of preshaping can alleviate the instability and unbalancing effect for multi-finger grasps due to the different timing of the fingers' contact to the grasped object, especially for those low-weight objects. This is a special demand, particularly for robotic prosthetic hands. For robot hands, their fingers can be individually controlled to adapt to the profile of an object by regulating the speed of each finger. However, this approach is impractical for prosthetic hands since they are all gesture-based controlled robotic hands. Although an additional vision system can be added to detect the object's profile and regulate each finger's movement (i.e., like a robot hand) it brings extra complexity and computational burden to the overall system, in addition to contradicting some basic rules for designing a prosthetic hand, i.e., low weight and low cost. Also, there is another approach to possibly alleviating such an issue. A user can adjust each finger's position by performing some prior gestures and accordingly adjusting the whole hand's orientation so that the pre-grasp position of the hand can perfectly fit the profile of the object. Apparently, finding an optimal pre-grasp position for each object can greatly increase the cognitive load for a prosthetic hand user. Together with excessive training, it can significantly discourage them to use robotic prosthetic hands with PR control. Moreover, the amount of improvement by training is not guaranteed since the ADLs involve a much uncontrollable environment compared with training classes or laboratory environment.

Therefore, the preshaping capability demonstrated in this work is a simple and effective way to improve the tolerance for maintaining the stability and quality of the multi-finger grasps (i.e., pinch, power grasp), especially with a prosthetic hand operated using a PR control system in real life.

B. Multi-Stage Grasps

There are potentially many more combinations of grasps that allow different multi-stage grasps in addition to the ones demonstrated this work. Besides, not only two-stage but also three-stage grasps are possible to suit the specific needs of each prosthetic hand user, which can greatly augment the dexterity and capability of the hand in terms of grasping diversity.

The use of multi-stage grasps is expected to be a personal choice based on the preferences of a user since each user has individual needs in practice. The amount of needs can affect the amount of practice required and consequently affect the proficiency when it comes to operating multi-stage grasps.

Besides, proficiency in using PR control for separate gestures is a pre-skill for a user, which can greatly affect their confidence and aspiration to achieve multi-stage grasps. As the relevant techniques advance, PR control is expected to become more popular in clinical settings with more efficient training procedures developed by joint efforts among all the stakeholders such as users, therapists, prosthetists, medical doctors, researchers, and engineers. This will significantly help users to comfortably learn and master PR control.

VI. Conclusion

In this work, a 3D printed soft robotic hand with embedded soft sensors, intended for prosthetic applications, is developed to efficiently operate with pattern recognition based myoelectric control systems. Pneumatic chambers are designed to be embedded within the fingers and thumb, working as flexure hinges for the joints and soft position sensors simultaneously. The whole hand can be 3D printed monolithically and require minimal post-processing for the addition of its embedded sensors. These characteristics are significant a bionic for a bionic device that is required to be lightweight and anthropomorphic. The mechanical structure of the hand was fabricated by using a low-cost and open-source 3D printer.

With the addition of position sensors, self-collision can be avoided and therefore the neutral fully-opening position can be eliminated for switching between different gestures. This makes the transition between hand gestures much faster, more efficient, and more intuitive as well. Besides, initial contact detection of each finger/thumb is enabled to achieve preshaping of multi-finger grasps (i.e., tripod grip and power grasp). This can considerably alleviate the issue of grasp instability due to a grip force imbalance which is the result of the fingers of the hand reaching the hand at different times. The inclusion of preshaping allows the hand to achieve form closure of a grasped object readily, which greatly improves the stability and quality of the hand grasps.

Last but not least, the free transition between gestures allows the hand to perform multi-stage grasps by combing different grasp types sequentially so that the hand is not limited to carrying or holding one object at a time, which improves the hand's dexterity and grasping diversity, rendering this soft robotic hand one step closer to its biological counterpart.

Future work aims to optimize the soft robotic hand in terms of grip strength, grip speed, and lifespan. Also, the motor-pulley system will be upgraded and the self-collision avoidance routine will be repeatedly tested to ensure that the hand's grip time does not exceed the response time of the fail-safe procedure. The real-time internal processing of data will be optimized to make sure it is compatible with specific PR control systems. To translate the 'ACES-V2' hand for prosthetic use in practice, its reliability and robustness will be investigated through an interactive design process to be guided by clinical trials.

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