

Integration of an Adaptively Reconfigurable Compliant Anatomical Palmar Mechanism with Multi-DOF Robotic Finger Grasping

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Abstract: The primary focus of robotic hand design has been placed on integrating a series of rotational joints at each finger. The paper presents the design of a compliant anatomical palmar mechanism (CAPM) that augments the robotic hand's capabilities by adapting between precision and power grasps. A design of this robotic hand has been developed based on the anatomical inspiration of the human hand to find a direct relationship between palmar deformation and the rotation of the fingers at a shared joint. Palmar deformation has an effect on the orientation and position of the fingertip's location when contacting a target object. Previously determined simulation results of this geometrically complex, large displacement, hyper-elastic structure are compared to initial experimental results to show simultaneous varied conformity of the palm.

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1. INTRODUCTION

Human hands simultaneously demonstrate dexterity and powerful grasping of objects across a range of complex tasks. Creating anthropomorphic robotic hands generally focuses on the former, relying primarily on multiple fingers with redundant muscular motors to achieve a higher degree of manipulation. Therefore, conventionally the design objectives of a robotic hand are on the positioning of the fingers relative to the target object to maintain a stable grasp and often neglect the functional role of the palm. The palm is less well understood and has been underexploited in its role to enhance a robotic hand's functionality spectrum. Studying the relationship between the palm and the fingers, and the use of both in conjunction could augment versatility in grasping configurations. This paper presents how the design criteria previously derived from a study on the anatomical structure of the human palm can also be applied to the fingers. The design of both can be prototyped to perform tasks that require adaptability in partially unstructured environments.

The role the palmar region plays ranges from enhancing the dexterity of fingers or providing flexibility to the way researchers design hardware built into the hand itself. To account for novel actuator arrays or other electronic components to drive the motors, the space within the palm itself is utilized to drive multiple fingers for compact operation (Rosmarin and Asada 2008) (Liu et al. 2008) (Carozza et al. 2005). Extendable, telescopic actuated soft palms are also implemented to prevent collision with sensitive sensors in this same palmar region (Meng et al. 2020). Additionally, the palm has been considered to broaden finger dexterity. A criterion to evaluate dexterity, thumb opposition (thumb opposing or touching other fingertips) in the BCL-26 robotic hand, incorporates a multi-DOF palm that rotates the thumb to achieve this (Zhou et al. 2019). RBO-Hand-2 also incorporates the opposable thumb, including two extendable actuators in the palm. A compliant fiber-reinforced silicone transmits forces between the palm and the fingers to increase stability for power grasps or heavier loads (Deimel & Brock 2014). To augment

versatility in the hand and dexterity with the fingers, reconfigurable palms have altered their topological structure by having additional DOF to the thumb (Wei et al. 2011) (Aukes et al. 2012).

In mechanical system design, when considering the palm's contribution to grasping configuration, certain assumptions have been made to reduce the complexity of modeling the multi-layer human palm into a tractable form. Characterizing the palm as a flat surface is an assumption some studies have rejected as an accurate interpretation of how palmar opposition increases stability in grasps. A study on palm concavity compares the effect of fixed and curved 2DOF palmar surfaces on the performance of a human hand when grasping various geometrical objects such as pyramids, cylinders, and spheres. The adaptable palm that emulates the motion of the thenar and hypothenar muscles yields improvement when studied against the fixed palm in grasping the sphere, pyramid, and small cylinder (20mm diameter) (Morales et al. 2020); the results suggest various palmar angles in each distinguishable condition, implying inadequacy of estimating the palmar region as not only a level surface but also as a fixed curved area (Liu et al. 2008). However, examining the results of arch shape modulation using the dorsum (posterior) part of the hand, the inner arch movement incorporates complications of intrinsic muscle and thickness variations. Some researchers assume the flat nature of the palmar region, instead actuating the active palm to translate vertically outwards to move the center of mass of the object to alter the contact location for the fingers (Pagoli et al. 2021).

The human hand exhibits the importance of interchangeability between grasps on a day-to-day basis. For example, some tasks require the hand to adapt throughout the grasp such as tightening a jar lid: the palm is used to apply torque while the dexterity of the fingertips is required to align threads with less dependency on torque output (Cutkosky 1989). These observations suggest that the conventional evaluation benchmark, which concerns the positioning of the fingers relative to the target object to maintain a stable grasp, is necessary but not sufficient. Unable to account for the wide

range of complex activities that humans participate in daily, unknown external forces may destabilize a system or tasks may evolve and/or require variable forces.

Grasp taxonomy has categorized two major groups of tasks as illustrated in Fig. 1(c): precision manipulation and power grasp. The distinction between them has been interpreted in various ways by researchers; discerning precision handling as an intrinsic movement of the object independent of the arm compared to a rigid relationship between object and hand in the power grip (Landsmeer 1962) which is used primarily by the fingers. Other definitions include describing a precision grip as pinching of the target object between flexed fingers and the thumb; a power grip is clamping of the flexed fingers and the counter pressure of the thumb and palmar region (Napier 1956). Dependent on the nature of the task and the geometry of the target object, tasks may require precision, power, or a combination of both grasps. While depending on the accuracy of the robotic fingers is crucial for tasks that require a high level of precision, there is a disposition of under-valuing the palmar region: a critical component of the human hand needed for power grasps. The prevalence of the palm's use in conjunction with multi-DOF fingers can add to the versatility in the function of a robotic hand to perform various tasks.

2. ANATOMICAL DESIGN

Built upon a previous study on the human anatomy and certain assumptions made to develop a robot hand, the design of a palmar mechanism was created to form power grasping configurations (Chang and Lee 2023). Fig. 1 shows the sectioning of the bone structure (Fig. 1a) for the fingers (phalanges) and palm (metacarpal). The observed relationship (Fig. 1b) between these parts defines the surface deformation of the compliant anatomical palmar mechanism (CAPM) when used in conjunction with the fingers to form precision/power grasping (Fig. 1c). The illustrated example shows a conforming palmar surface about a rigid spherical object. The metacarpal bone segments were modeled as equivalent beams (indicated as thick multi-colored-line segments).

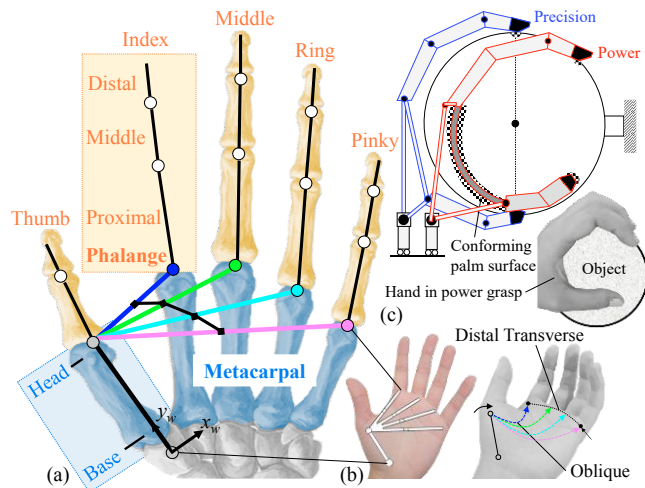


Fig. 1. Schematics illustrating the CAPM. (a) Human hand anatomy. (b) CAPM design concept. (c) Change of grasping configurations.

The paper discusses the following topics to explore the interdependent relationship between the fingers and CAPM:

- By analyzing the kinematics of the rigid robotic fingers based on DOF assumptions made at each part of the

phalange, determine the necessary joint angles to evaluate fingertip (endpoint) position in both precision and power grasping configurations.

- Based upon anatomical studies and observation, conceptualize and illustrate the relationship between the deformation of CAPM and the connecting joint to the multi-DOF robotic finger.
- Compare previously found simulated deformation results of the CAPM hyper-elastic surface through demonstration of an actuated assembled prototype.

2.1 Robotic Finger Kinematics

In both precision and power grasping formations, the fingers themselves establish multiple localized contact points along the surface of the rigid object. These rigid series of linkages are connected as shown in Fig. 2, assuming rotation or translation at each joint of the robotic finger. The thumb can rotate at the wrist in 2DOF, contrasting to the remaining fingers which are rigidly attached to a base frame.

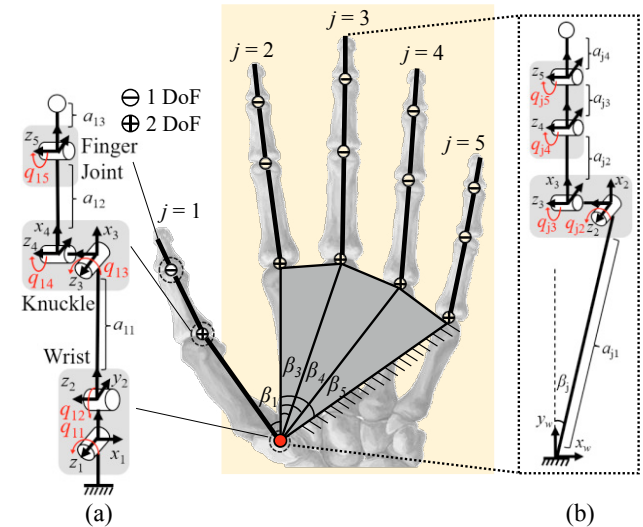


Fig. 2. Parameters and joints of the robotic fingers.

To describe the kinematics for the system, Denavit-Hartenberg (D-H) parameters are used for each finger j as seen in Table 1: α_{jn} for rotation in x at joint n , a_{jn} translation along x at joint n , d_{jn} translation along z at joint $n-1$, and q_{jn} rotation in z at joint $n-1$. β_j is the fixed angle locating the base of each finger relative to the wrist. The length of each segment of the finger is what determines a_{jn} while the unknown rotational joints q_{jn} are to be evaluated based on the specified grasping configuration (all the values of $d_{jn} = 0$, therefore are not included in the table).

These parameters determine the orientation and position of the fingertip in space to grasp the object when directly inputted into a series of transformation matrices defined for each finger j in (1) and (2).

$$[T_n^{n+1}] = \begin{bmatrix} \cos q_{jn} & -\sin q_{jn} \cos \alpha_{jn} & \sin q_{jn} \sin \alpha_{jn} & a_{jn} \cos q_{jn} \\ \sin q_{jn} & \cos q_{jn} \cos \alpha_{jn} & -\cos q_{jn} \sin \alpha_{jn} & a_{jn} \sin q_{jn} \\ 0 & \sin \alpha_{jn} & \cos \alpha_{jn} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$T_j = \prod_{n=1}^5 T_n^{n+1} = \begin{bmatrix} R(q_{jn}) & X(q_{jn}) \\ \mathbf{0} & 1 \end{bmatrix} \quad (2)$$

Table 1. D-H Parameters ($d_{jn} = 0$)

n	Thumb ($j=1$)			Finger ($j=2,3,4,5$)		
	α_{1n}	a_{1n}	q_{1n}	α_{jn}	a_{jn}	q_{jn}
1	-90	0	$90 + \beta_1 + q_{11}$	0	a_{j1}	$90 - \beta_j$
2	90	a_{11}	q_{21}	-90	0	$\beta_j + q_{j2}$
3	-90	0	q_{31}	0	a_{j2}	$-q_{j3}$
4	0	a_{12}	$-q_{41}$	0	a_{j3}	$-q_{j4}$
5	0	a_{13}	$-q_{51}$	0	a_{j4}	$-q_{j5}$

To evaluate the desired joint angles, the inverse kinematics problem is solved using (3) and (4) to determine the incremental joint angles needed to move the initial flat palm configuration position $\mathbf{u}_o$ to the desired fingertip contacting location $\mathbf{u}_d$:

$$[\mathbf{J}] (\in \mathcal{R}^{5 \times 1}) = \frac{\partial \mathbf{X}(q_{jn})}{\partial q_{jn}} \quad (3)$$

$$\dot{\mathbf{Q}} = [\mathbf{J}]^{-1}(\mathbf{u}_d - \mathbf{u}_o) \quad (4)$$

Similar to the proportional relationship between the parts of the phalanges and the overall size of the human hand itself, Table 2 shows the parameters for the fingers:

Table 2. Robot Finger Parameters

[mm]	Thumb	Index	Middle	Ring	Pinky
a_{j1}	80	128	136	144	144
a_{j2}	48	48	56	48	40
a_{j3}	48	32	40	32	32
a_{j4}	—	32	40	32	32
β_j	37°	0°	20°	40°	62°

An example of grasping a spherical object with a radius $r_s=72\text{mm}$ is used as an example problem in the desired configuration position to estimate joint angles. The desired endpoint position $\mathbf{X}_d$ of the fingers are shown in a power grasp. The contact points are assumed to lie in the same plane distributed across the surface. The center of mass (COM) located at $O[\text{mm}] = [50, 50, 100]$ is positioned from the wrist joint coordinate system $[x_w, y_w, z_w]$, as shown in Fig. 3:

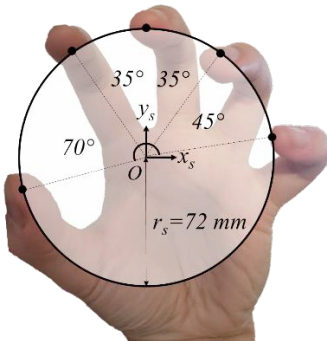


Fig. 3. Layout and distribution of the fingers grasping the spherical object across its surface, planar to the COM

Multiple solution reach the contacting points when solving the optimization problem to reduce error $\min \|\mathbf{X}(q_{jn}) - \mathbf{X}_d\|$. Therefore, joint angle limits $q_{jn} < 90^\circ$ are used as constraints when solving the inverse problem. MATLAB was used to numerically solve for the inverse kinematics using the finger parameters and the joint angles were found in Table 3:

Table 3. Joint Angles

	Thumb	Index	Middle	Ring	Pinky
q_{j1}	-3°	—	—	—	—
q_{j2}	-30°	23°	45°	-5°	25°
q_{j3}	30°	68°	49°	57°	64°
q_{j4}	44°	46°	50°	40°	25°
q_{j5}	88°	17°	53°	30°	30°

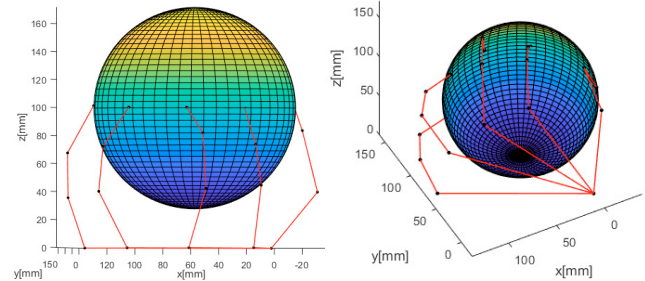


Fig. 4. Joint angles of the multi-DOF fingers grasping the object about its COM.

Determining a set of feasible joint angles to help visualize the bending to achieve this precision grasp makes for well-informed decisions related to the design of the robotic finger.

2.2 Cable-Driven Underactuated Finger Design

The example task of holding a spherical object to demonstrate CAPM's role in power grasping does not require a high level of manipulation. To reduce the number of required actuators, the robotic fingers are designed to be cable-driven. At the base of each finger, only one motor is required to curl the finger forward in a configuration that is similar to the angles expected from the inverse kinematics solution (Fig. 5).

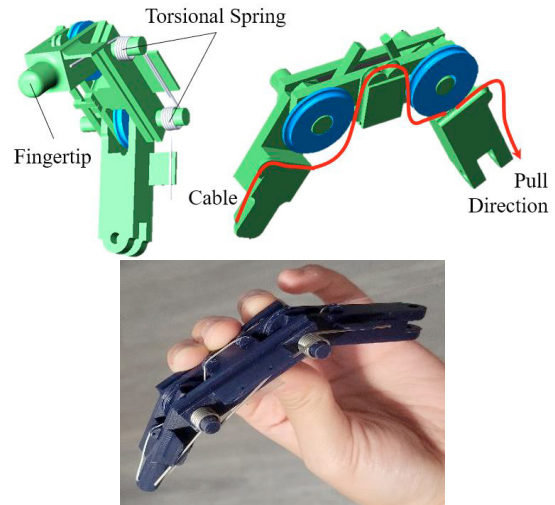


Fig. 5. CAD model and prototype of an underactuated robotic finger with a cross sectional view to show the threading of the cable

A cable is threaded in between a system of pulleys built into the series of rigid linkages of each finger. When the cable is pulled downwards, the line slips and the finger bends due to the shortened length. This configuration was inspired by the design (Mottard et al. 2017) of rotational sliding joints. 180-degree torsional springs with a constant 0.375 in-lb per rotation were chosen to maintain the straightened finger position when not actuated. An adjustable locking mechanism is incorporated to set the limitation on the maximum degree of rotation before the next joint in the series would start to rotate.

2.3 CAPM Design Summary

The human palm is a surface that seemingly deforms in a very complex manner. After studying the anatomy of the palm in relation to the underlying bone structure, the deformation of the palmar surface was simplified into a few parameters to make the mechanism mathematically tractable. The palm has been found to depend on a collection of arches that transverse across its surface shown in Fig. 6(a); oblique and distal transverse arching. Oblique arching was found to depend on the two degrees of rotation of the thumb (ζ, φ). Distal transverse is defined by the translation r_j of the metacarpal head when the fingers curl. When initially in a flat palm configuration, both arches are not activated (Fig. 6b). A common example to observe both arches in action can be seen during thumb opposition: when each finger achieves contact with the thumb at the fingertip (Fig. 6c).

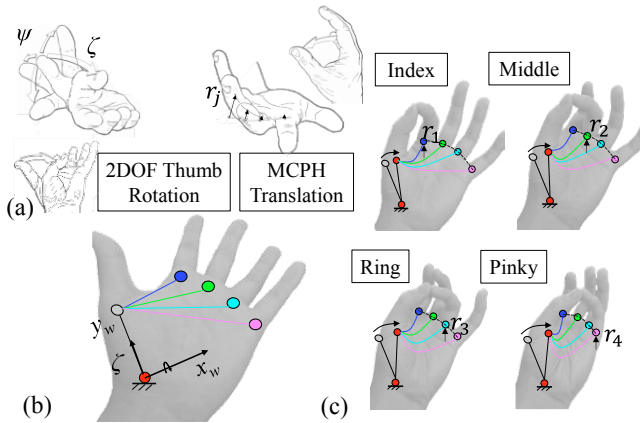


Fig. 6. Overview of CAPM's design with a) rotational and translational joints b) compliant beam structure layout c) highlighting finger opposition.

Replacing these arches with interconnected compliant beams form the overall structure of CAPM. Compliance is an advantageous choice for this design to reduce the number of joints to mimic continuous deformation of a surface. The mechanism itself is composed of a hyper-elastic material, chosen due to its advantages of recoverability and large deformation with its ability to conform to a surface. While CAPM can potentially be seen as an independently operating mechanism, studying its behavior at the base of the fingers can highlight an important relationship that may lead to developing an improved design.

2.4 Interconnected Components

Based upon the development of the design for CAPM, a few assumptions can also be made regarding the relationship between the palm and the fingers, founded in observation and anatomical studies. The metacarpal and the proximal phalange share a joint that is assumed to have two degrees of freedom. Illustrated in Fig. 7, when q_{j3} bends from 0° to 90° , the surface of the palm protrudes and translates away from the head of the metacarpal.

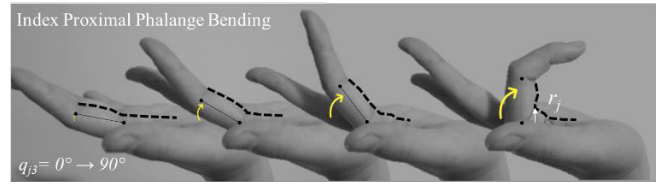


Fig. 7. Bending of the finger forward, or rotating q_{j3} , at each finger also affects the translation of the palmar surface

CAPM has been determined to require translation r_j at each endpoint of the cantilever beams, which is also naturally observed with the bending of the proximal phalange forward. A relationship is established: rotation of q_{j3} can be used to directly translate the cantilever beam. This observation reduces the required number of actuators needed for the operation of both components and leads to the conclusion of their interdependence. A Scotch-Yoke mechanism is incorporated at each knuckle of the robotic hand to turn rotation into translation, where $r_j = R \cos(\gamma)$ (Fig. 8):

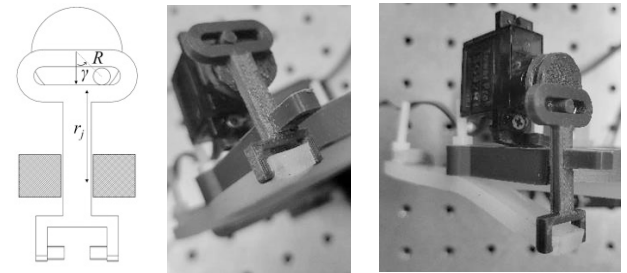


Fig. 8. Connection of the motor to the Scotch-Yoke to translate depending on the radius R and angle γ to translate r_j .

3. RESULTS

The range of motion of CAPM was found by obtaining simulation results in relation to the two types of input: thumb rotation and endpoint loading of the cantilever beams of the mechanism (Chang and Lee 2023). The robotic finger's positioning relative to an object is also dependent on the palm's deformation as interconnected elements as previously discussed. An initial prototype is developed to observe the deformation of CAPM relative to the 2DOF rotation of the thumb linkage. The buckling behavior in the mechanism is compared to previously found simulation results from FEM.

3.1 Experimental Design

The CAPM is made out of silicone rubber and was constructed using a 3D-printed mold. The dimensions of the interconnected compliant beams of length l_m are listed below and shown in Fig. 9:

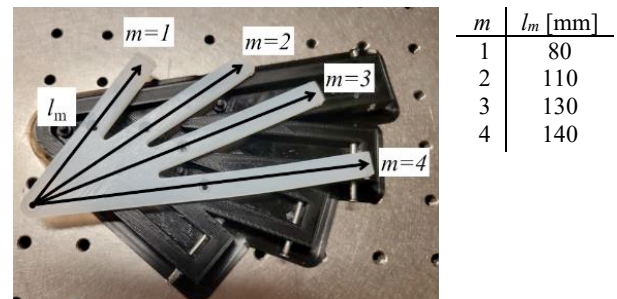


Fig. 9. Silicone rubber CAPM, a singular piece created out of a mold as an interconnected piece of four compliant beams of varied lengths

CAPM is fixed at the midpoint of each compliant beam with a rigid thumb linkage connecting it to two MG995 servo motors in series. The justification for using servo motors includes the advantage of built-in position control and higher torque in a limited angle of rotation application. The thumb linkage rotates in two angles (ζ , φ) which determine the shaping of palmar region. The hardware layout is illustrated below (Fig. 10):

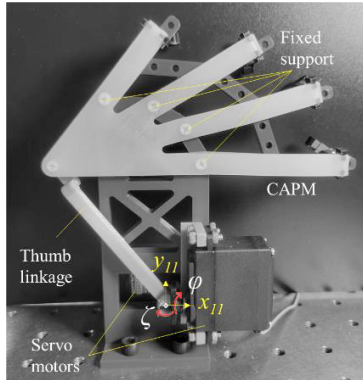


Fig. 10. Silicone rubber CAPM, a singular piece created out of a mold as an interconnected piece of four compliant beams of varied lengths

3.2 Palm Deformation

An initial experiment was conducted to shape the palm by incrementally adjusting the rotation angles of ζ , φ within a range of 0° to 30° using a potentiometer and observing its effect on the deformation of the hyper-elastic mechanism and determine its range of motion (Fig. 11).

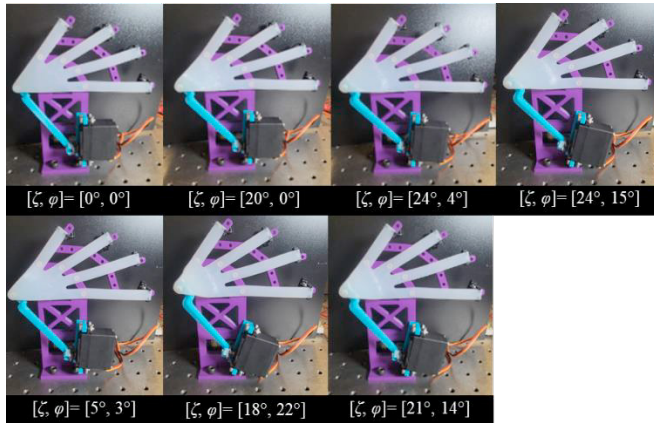


Fig. 11. Initial experimentation results of deforming CAPM in two degrees at the wrist joint.

When compared to previously obtained FEM model simulation results of CAPM when a combination of rotation angles between 0° to 15° were applied, similar multi-modal buckling behavior is seen near the connecting point between the thumb linkage and the palm. The chosen upper limitation on rotation angles was determined by the choice of motor and the amount of torque that can be provided, concluding that this is the maximum amount of deformation that CAPM can experience in this current hardware configuration.

A top view of the deformed palm (Fig. 12) shows the protrusion of the flat palm from its initially planar state as a

potential contacting region to cup the target object from three sets of rotation angles $[0^\circ, 0^\circ]$ $[14^\circ, 24^\circ]$ $[24^\circ, 33^\circ]$.

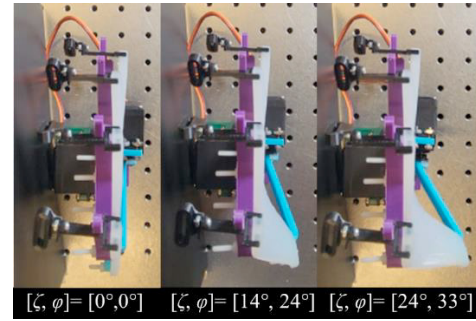


Fig. 12. Top view of the deformation of CAPM protruding from its initial flat palm state.

CAPM has the ability to return to its original flat palm configuration (rotation angles $[0^\circ, 0^\circ]$), attributed to the choice of using a hyper-elastic material such as silicone rubber. Through several trials of this experiment there was minimal tear, however the durability of such a material over time has yet to be tested if needed in specific applications of constant repeatability. When contacting objects during grasping, the deformation of CAPM can change therefore the shaping of this mechanism is assumed to take on this form only to observe the forward kinematic effects of the joints.

4. CONCLUSION

This paper reviews the design process and assumptions made regarding the development of the fingers of a robotic hand with an integrated compliant anatomical palmar mechanism (CAPM). The anatomical inspiration design method was applied to all parts of the system from the DOF assumptions of each joint to the interdependent nature of the palm deformation from the finger joints. In doing so this complex anatomical feature is simplified to a deformed surface that depends on a collection of rotational and translational joints that affect the endpoint positioning of the fingers. Prototypes of the silicone rubber CAPM were constructed out of a 3D-printed mold. The previously obtained simulation results of an elastomer are compared to hardware experimentation capturing the deformation of the palmar surface. Future work includes using sensors to determine the expected forces at the contact points of the object to understand the effect the addition of CAPM has on increased grasping stability.

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