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Patterned Compliance in Robotic Finger Pads for Versatile Surface Usage in Dexterous Manipulation

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***Abstract*— The design of finger pads for robotic and prosthetic hands is often overlooked, with relatively simple shapes and mechanical properties typically used. The finger pad geometry and mechanical properties are especially important for within-hand dexterous manipulation, and human finger usage patterns suggest extending robotic finger pad usage onto side surfaces could enable a wider range of manipulation motion. In this work, we propose a novel finger pad design that combines a ridged stiff inner structure with air gaps and a flexible outer skin to facilitate both grasp stability and versatile usage of the finger surface. The air gaps enable objects to displace the outer skin and stably settle between two adjacent ridges. During manipulation, the ridges can also serve as predictable pivot points. Experimental results comparing three ridged finger designs to a conventional solid core design show that the ridged designs consistently outperform the reference solid core design for all objects, in terms of the ability to stably manipulate objects through a large motion range without ejection (losing grip on the object). Designs with larger spaces between ridges performed better overall than designs with closer spacing, showing that larger "wells" allow objects to more stably settle into the space between ridges. We anticipate the novel finger pad designs and the analysis of their behavior will inform future robotic hand designs, especially designs which aim to incorporate side finger usage.**

I. Introduction

While some works have analyzed shape considerations for robotic finger pad design (e.g. [1], [2]), many robotic hands (e.g. [3]–[5]) still use simple flat finger pads. This is likely because flat finger pads offer stable, predictable grasping and manipulation behavior and are easy to construct. However, using planar finger surfaces can limit dexterity, making it more difficult to stably roll the object towards the sides of the fingers, which are often utilized heavily during within-hand dexterous manipulation [6]. Rounded or anthropomorphic (e.g. [7]–[9]) finger pad shapes may enable a wider range of motions, but the rounded shapes can also make stable, robust manipulation more difficult.

Studies of human manipulation provide some motivation to enable robotic manipulation using a wide variety of finger surfaces. An experimental study of human precision manipulation [10] shows that humans frequently use the side surface of their index and middle fingers during precision manipulation. A study of human grasping [11] shows also that the lateral pinch grasp, where the thumb is pressed against the side of the index finger, is a particularly versatile grasp, further highlighting the importance of lateral finger usage in human hand use. The lateral pinch is used frequently in daily tasks such as inserting keys, or grasping other thin, flat objects. The extensive finger side surface use suggests that the fingers can be used effectively in a bracing role, where the passive stiffness of the finger is being used to apply forces in a direction the finger cannot be actively actuated in. This type of strategy can reduce actuator torque requirements and energy consumption during manipulation. Overall, human finger side surface usage suggests robotic fingers designed for dexterous manipulation could also benefit from enabling more versatile usage of the finger surface.

Figure 1. Novel finger pad designs and conventional cylindrical solid core design for comparison. In this work, we discuss the core design as part of the overall finger pad design, since the core structure influences the finger pad's mechanical properties during grasping and manipulation.

This work investigates a novel approach for finger pad design that balances some of the stability characteristics of flat finger designs with the versatile surface usage of rounded or anthropomorphic designs. Specifically, we propose a finger pad with alternating ridges and air gaps, along with a flexible rubber shell. Some example proof-of-concept finger pad designs are shown in Fig. 1. These novel finger structures enable stable balancing of an object across two points (similar to a flat finger), repeatable pivoting using a single point, and a desirable caging behavior [12], where the object corner or a curved object surface indents the finger pad and is stably held by two points simultaneously.

This paper is structured as follows. A summary of background and related work in presented in section II. Section III details the general approach, overviewing the desired properties of a candidate finger pad and the configurations examined in this investigation. An experimental evaluation of the current designs is described in section IV, followed by a discussion of the results and future directions in section V.

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II. BACKGROUND AND RELATED WORK

Very few previous works use a purposefully shaped internal rigid structure with air voids or other zones of high compliance to enhance the performance of the finger pad during manipulation. One related work did look at adding a single air pocket to a prosthetic finger to enhance the finger pad compliance [13]. Another work looks at modifying the structure of the outside rubber shell of a finger pad [14]. This work is probably the most closely related to the current work, and shows that the force-displacement relationship can be modified based on the structure of the external rubber shell. However, that work differs from the present one in that it only discusses modifying the flexible outer shell rather than the rigid internal structure, and also focuses on much smaller scale structural modifications. In fact, it may be possible to combine the that approach with the current one by using the type of internal structure proposed in this work to affect larger scale manipulation behavior, and the rubber structures proposed in that work to fine tune the external shell behavior.

Some previous works have considered robot finger pad materials and geometry. An analysis of the desirable mechanical properties of six materials for robotic finger designs found that sponge and gel are favorable materials for the interior of finger pads [15]. Some analysis techniques applicable for soft fingers during manipulation can be found in [2], [16]. Designing finger pad external shape based on the geometry of the manipulation is discussed in [1].

In general, many implemented finger pad designs use simple layered structures, usually with fairly uniform wall thickness in each layer, rather than purposefully modifying the internal support structure shape as in the current work. Many designs use plastic cores with an outer rubber shell or rubber pad (e.g. [3], [17], [18]). Other designs use rubber outer shells filled with other materials, such as in [19].

In many cases, robotic finger pads are designed for their sensing properties rather than their mechanical properties during manipulation. For example, a number of different robotic "skins" have been developed for sensing applications and are described in [20]. An example of a robotic finger pad developed with sensing in mind can be found in [21]. The current work differs from these approaches by using finger pad structure to enhance the mechanical behavior of the finger pad during manipulation.

There exist some whole finger designs with interesting properties that could potentially be adapted to the scale of a single finger segment as well, but with considerable mechanical complexity. For example, the Festo FinGripper [22] has favorable adaptive properties that may be usable on a single finger segment. The distinction between the entire finger and a finger segment can potentially become blurred, as with the theoretical example of a "fractal" manipulator discussed in [6]. However, scaling a full finger design down to the scale of a single finger segment could pose many challenges, thus it is worth considering simpler static rigid structures as well, as in the current work.

Overall, other works on robotic finger pad design generally focus on external finger shape, overall materials, and sensing properties. Most implementations use simple layered structures with fairly even wall thickness throughout a given layer. The current work differs from these other works by focusing on modifying the rigid internal structure of the finger pad to benefit manipulation performance.

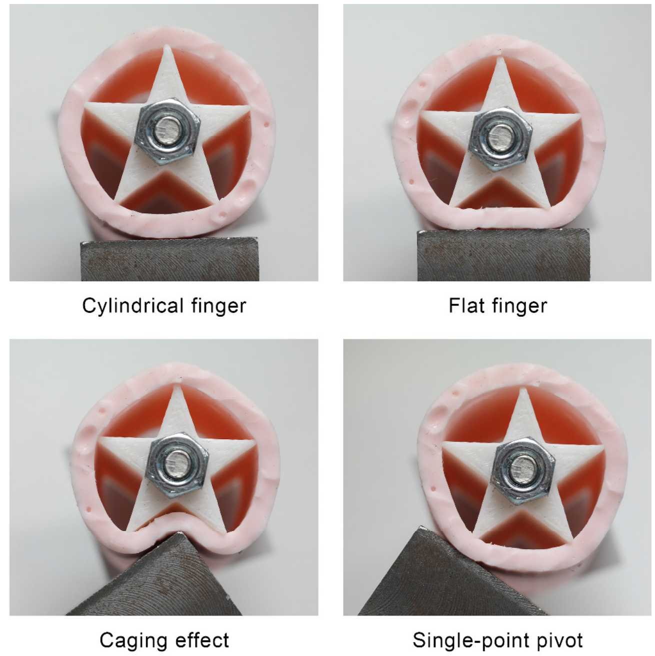

Figure 2. Four example behaviors that the finger pad design exhibits. Under low forces, it can act as a cylindrical finger. With higher forces, it can either act as a flat finger or provide a caging effect, depending on the object geometry. Finally, during manipulation, the object often pivots around a single point on one finger.

III. PROPOSED FINGER PAD DESIGN APPROACH

The chosen finger pad design approach involves using a carefully chosen rigid skeletal structure along with air voids and a flexible skin to balance grip stability and manipulation versatility of the finger. In this work, we focus on simple proof-of-concept designs (Fig. 1) to enable finger side surface use, with some inspiration from human side surface use during manipulation [10] and the versatility of the lateral pinch grasp, which uses the side surface of the index finger [11]. However, a similar technique could be applied to facilitate other types of manipulation. We will first present our goals and hypotheses for the functionality of the proposed design, and then discuss a simple experiment used to assess the performance of the design.

The overall functional goals are to achieve both stability and versatility. Stability can be assessed by whether the object is ejected during a repeated series of motions, and versatility here will be defined by the angular range through which stable manipulation is feasible, for a given pair of fingers and object. If manipulation can be performed many times in a row without ejection, we will also describe the motion as being fairly repeatable or robust.

We hypothesize that the chosen finger pad designs will achieve stability and versatility in a few different ways. Stability can be achieved in multiple ways, as shown in Fig. 2. Under low forces, the finger may behave similarly to a

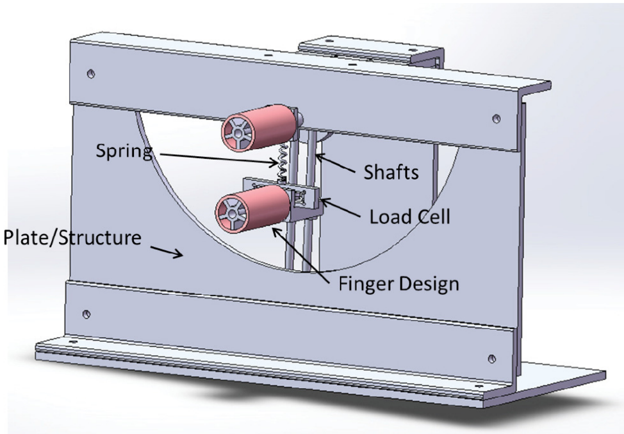

Figure 3. Finger testing apparatus. A motor actively rotates the bottom finger, with the rotation axis through the top, static finger. The spring allows passive motion in one additional degree of freedom.

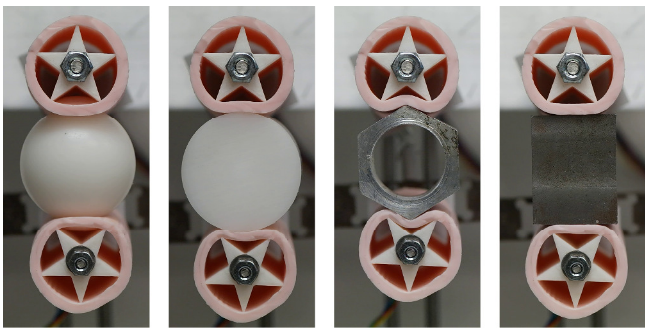

Figure 4. Initial object positions during manipulation. Note the initial position of the hexagon object, which was chosen to better test the caging behavior of the finger pads.

cylindrical rubber finger. With a larger flat object surface in contact with the finger and slightly higher forces, the object should settle against two points, making the functionality similar to a flat finger. If the object shape at contact is convex or a sharp corner, then the rigid points should perform a caging role, and the object should displace the rubber skin and stably settle somewhere in between the two rigid points. This settling behavior could help reduce variability caused by object slip [23] observed during dexterous manipulation.

During manipulation, the object will transition between these different contact conditions. The points of the rigid structure, in addition to acting like a flat finger or working together to "cage" an object, can also act as a pivot point during manipulation. We anticipate a tradeoff here in the number of points – with few points, the object will be quite stable in between a set of points, but it will be difficult to move to another set of points, while with many points, it will be easier for the object to move through a wide angular range, but it will likely be less stable, and the finger properties will approach those of a conventional solid finger with an elastic shell.

Overall, we expect that the novel finger structure will help keep the object stable by providing compliant regions for the object to settle into, producing either a caging effect or a flat-finger like effect. In addition, the points of the rigid structure should provide natural pivot points for repeatable manipulation motions. However, points could also act as

TABLE I. PROPERTIES OF OBJECTS TESTED

Object Name	Object Properties		
	Weight (grams)	***Dimensions (cm)***	***Material***
Sphere	39	3.8 diameter	Delrin
Cylinder	55	3.8 diameter 3.4 height	Delrin
Hexagon	23	3.2 flat-to-flat 1.9 sides	Aluminum
Rectangle	167	2.3 x 2.7 x 3.5	Steel

barriers when moving through a larger angular range which would cause the object to move past a point, so we anticipate there will be an ideal number of points which gives adequate stability, while not making transitions through a wide angular range too difficult.

IV. EXPERIMENTAL INVESTIGATION

The overall goal of the initial experiment is to determine whether the novel finger designs can achieve stable, repeatable manipulation motions with a range of object geometries. The experiments also help to determine whether the hypothesized behavior of the finger pads, such as caging of an object between two adjacent rigid peaks, is observed.

A. Methods

To better isolate and understand finger pad performance itself, a controlled test setup was constructed to produce a precise, repeatable manipulation motion. Especially with compliant hand designs, the coupled behavior of the hand and finger pad system could make it difficult to understand the effects of the finger pad itself. The stability and robustness of the manipulation are assessed by determining how many manipulations can be successfully achieved through a specified angular range without object ejection.

1) Apparatus

Four different finger designs are tested, and can be seen in Fig. 1. Each finger has a solid ABS plastic core where the points or outer extent of the core structure lie on a 2.5 cm (1") diameter by 6.4 cm (2.5") height cylinder. These core shapes are chosen to allow comparison of point shape (star vs. five point) and number of points (five point vs. seven point), as well as comparison of all the novel designs to the prevalent design of a rigid core with flexible skin (cylinder). Each pair of finger cores is used with two soft silicone rubber (shore 20A) skins with 2.5 cm (1") inner diameter and a thickness of 3 mm (1/8"). The same silicone skins are used for each set of finger cores to isolate the effect of the shell structure. One finger with a simple cylindrical core is used as a control to compare performance to a more frequently used robotic finger design. Each finger is clamped securely to the testing apparatus during use – finger rotation was allowed during some initial testing prior to the experiment, but observed to often lead to instability and object ejection.

The manipulation apparatus shown in Fig. 3 is used to move the fingers during the experiment. Specifically, the

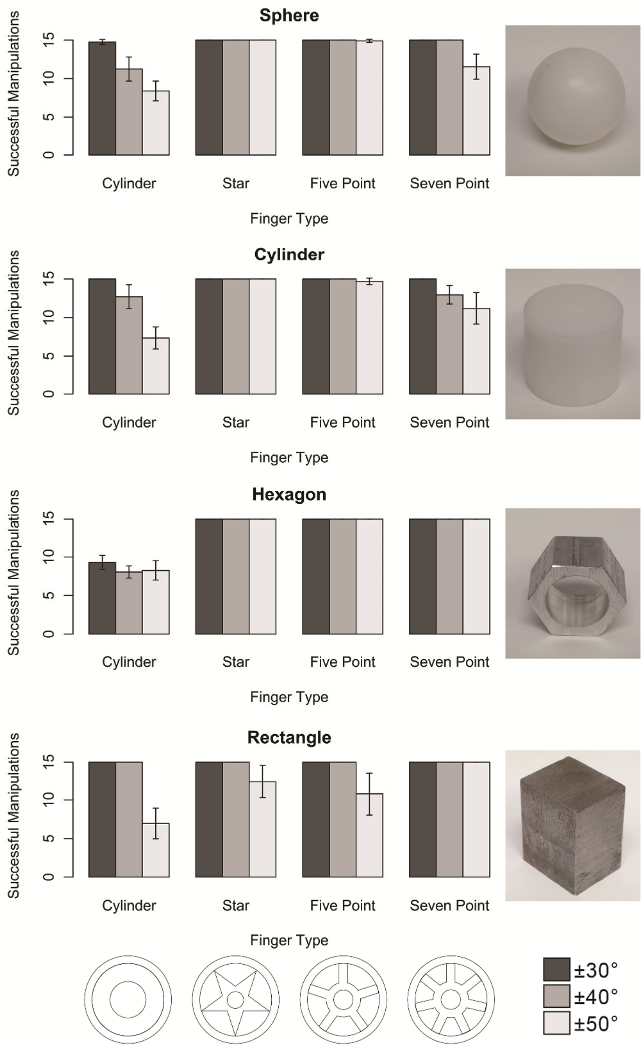

Figure 5. Results of the experimental trials. The number of successful trials completed is shown for the four different finger geometries and four objects tested. Error bars are 95% confidence intervals based on standard error.

device has one active degree of freedom (DOF), powered by a DC gear motor with a 64 CPM encoder, which rotates the mobile finger around a static finger, with the axis of rotation through the static finger. In addition, the separation of the fingers is allowed to vary passively with a single translation DOF, with a spring applying the required grip force. A load cell in line with the spring measures the grip force used, which was about 10-15 N during this experiment. A National Instruments USB-6212 DAQ is used to control the motor and acquire data.

Four objects are tested with each finger. Their properties are described in Table 1. The object shapes and their initial manipulation positions are shown in Fig. 4.

2) Procedure

Each of the three novel finger designs and one conventional design is tested with the four test objects as follows. At the beginning of a trial, the apparatus is initialized so that the mobile finger comes to rest directly below the static finger. The experimenter then pulls the fingers apart and places the object in the appropriate initial position indicated in Fig. 4. The object is placed half way along the length of the fingers to avoid any odd effects toward the ends of the fingers. Note that some figures have the object toward the end of the finger pad instead – this is simply for illustration purposes to better show the displacement of the finger pad. The object is then held in place by the spring force.

Once the object is placed, the mobile finger rotates back and forth with a sawtooth pattern for the target angle. Angle ranges of $\theta = \pm 30°$, $\pm 40°$, and $\pm 50°$ from the vertical angle are used for each finger-object pairing. An angular velocity of 3 radians per second defines the slope of the sawtooth motion pattern. We define one manipulation as one full period of the sawtooth. 15 periods of manipulation motion are performed for a given trial. If the object falls, the current manipulation cycle is recorded. Otherwise, a score of 15 manipulations is recorded if the full 15 repetitions do not result in object ejection. For each finger-object combination, 10 trials of 15 repetitions are performed.

B. *Results*

The composite results from all 480 manipulation trials are shown in Fig. 5. In the analysis below, p-values are calculated using an independent two-sample t-test (unpaired). Across all objects, the mean number of successful manipulations achieved is 11±0.7, 14.8±0.2, 14.6±0.3, and 14.2±0.3 for the cylinder, star, five point, and seven point fingers respectively. In this composite score, the three novel finger core designs all perform significantly better than the conventional cylinder core ($p < 0.001$). The composite score difference between the star and seven point fingers is significant ($p = 0.006$). However, the difference in overall scores between the five point and seven point fingers is not quite significant ($p = 0.09$). In addition, the difference in composite scores between the star and five point fingers is not significant ($p = 0.37$). Thus, overall the star has the best performance and is significantly better than the seven point design, but is harder to distinguish from the performance of the five point design.

The results can also be broken down by individual object types. For the spherical object, the star and five point fingers both perform significantly better than the seven point design, with $p = 0.007$ and $p = 0.009$ for the respective comparisons. The star, five point, and seven point novel designs all perform significantly better than the reference rigid cylinder core design ($p < 0.001, p < 0.001$, and $p = 0.002$).

For the cylinder object, only the star and five point designs perform significantly better than the conventional cylinder design overall ($p < 0.001$). The star and five point performance is also significantly better than the seven point finger performance in this case ($p < 0.001$). It is worth noting that for the 50 degree case, the seven point finger does perform significantly better than the cylinder reference finger ($p = 0.008$).

For the hexagon, it is worth noting that the object is placed initially with its points against the finger pads, rather than with the flat surfaces along the finger pad. Thus, the hexagon trials can help to assess whether the object's edges

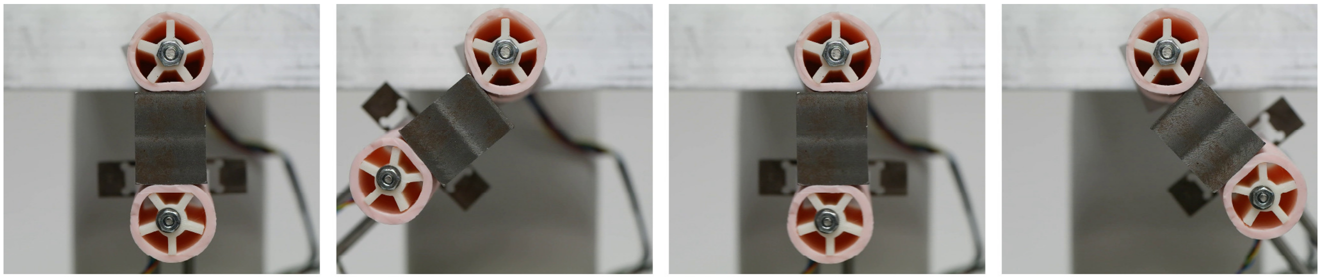

Figure 6. Video snapshots from an example manipulation with the five point fingers and the rectangular object. Time progresses from left to right. Initially, both fingers balance the object across two points, acting similar to a flat finger. Next, the object is pivoted onto the left point of the static finger. The object briefly passes through the initial position with all four points in contact, and then finally pivots onto the right point.

stably settling into the gap in between two finger ridges in the novel finger designs helps to improve manipulation performance. In this case, all of the novel finger structures perform quite well, and all are significantly better than the reference cylinder core structure ($p < 0.001$).

Finally, for the rectangular prism object, all finger designs perform the same for the 30 and 40 degree cases, but differently for the 50 degree case. All of the novel finger structures perform better than the conventional cylinder design for the 50 degree case (star: $p = 0.002$, five point: $p = 0.04$, seven point: $p < 0.001$). There is no statistically significant difference between the star and five point performance, but the seven point design in this case is actually significantly better than both the star ($p = 0.04$) and five point ($p = 0.01$) designs. This is the only test case where the seven point finger is significantly better than the two other novel finger designs.

V. Discussion

Overall, the novel finger pad designs with a pointed solid structure and air gaps perform significantly better than the reference solid core finger pad design. The novel finger pads do exhibit the expected behaviors, including providing stable regions for the object to settle into, providing a "caging" effect with two points and certain objects, providing a flat-finger like two point support for larger objects, and providing clear pivot points for the object to rotate around. However, the experimental results also highlight the complexity of each type of behavior, the effects of particular objects and angular ranges, and some of the resulting tradeoffs in finger design.

The novel finger pads do allow object edges to displace the silicone shell and settle stably into the space between two adjacent rigid points. This is best shown by the hexagon data, where the object is initially positioned with the points sticking into the finger pad. With the conventional solid core design, stable manipulation is significantly more difficult, as shown by consistently early ejection of the object. With the cylinder and to some extent also the sphere, it appears that with seven points, the point spacing may be too close to allow the object to stably settle into the smaller inter-point gaps, shown by the worse performance of the seven point finger for these objects.

For objects where the grasped surface is locally flat, the novel finger pads are able to provide similar behavior to flat fingers. This is shown by the rectangular prism manipulation, which starts with the object grasped across two points on both fingers. During manipulation, the mobile finger continues to have two points against the object, while the other finger transitions to other contact states.

Specifically, the rectangular prism manipulation is one example showing the ability of the finger pad points to establish consistent pivot locations for the object during manipulation, as shown in Fig. 6. As the mobile finger starts moving, the static finger transitions from the initial two point support to a single point pivot. When the mobile finger sweeps back through the initial position and toward the other direction, the rectangle transitions back to two contacts, and then the second contact now serves as a pivot point when moving in the other direction.

Analyzing each type of finger behavior reveals important tradeoffs for future finger designs which use a similar construction technique. Three main effects are considered in this experiment: the effects of point shape, point spacing, and object geometry. For point shape, little difference was observed between the five point design with flat points and the star design with sharp points. This may indicate that the exact shape of the points is not critical for design, likely partly due to the fact that the exterior of the silicone skin generally does not form sharp points even if the interior is quite pointed. Thus, with a thinner exterior skin, point shape may become a more critical design factor.

Ideal point spacing is dependent both on object geometry and the angular range of the manipulation. Overall, the five pointed designs with wider spacing performed better than the seven point design, with the better performance suggesting that the sphere and cylinder are better able to stably settle into the gap between two adjacent points. However, for the hexagon, the performance is comparable, and for the rectangle, the seven point finger pad actually performs better. For the rectangular prism, the greater number of points may make it easier to transition stably across points.

Overall, ideal finger pad shape will always depend partly on object and task. For example, for smaller objects, a finger design with more points may be suitable since the small object can still stably settle into the space between points, and the small inter-point spacing will make the transition between points easier. With the discrete point spacing, the angular range of the task can also play a large role. For example, small manipulations of only a few degrees could be performed without crossing points, whereas for large amplitude manipulations, the interaction between object shape and point spacing will become more important.

Some limitations of the current novel designs and experiment will now be addressed, as well as future work. The interaction between finger structure and object shape can be complex, and further analysis may be required to fully understand the design tradeoffs involved. The current experiment analyzes point shape and spacing effects, and demonstrates that the novel fingers can perform several large amplitude manipulation motions stably, but the effect of other variables could also be tested, such as the thickness of the outer skin or the material used. Some adaptation of the current designs may be required for implementation in a compact robotic hand. For example, some tapering of the shape may be desirable for fingertips, and space will have to be allotted for wiring and actuation.

Finally, one major area for future work is adapting and testing the designs beyond the planar manipulation motion considered. For example, if ridges are added along a second orthogonal axis, manipulation stability in additional directions may also be proved. A design using pins on the inner core rather than linear ridges could also be tested. Overall, even if the core air gap geometry is not selected with a specific manipulation motion set in mind, the ability of the object to be caged by sections of the finger pad or supported across ridges could still be beneficial and provide improvements in manipulation stability relative to a rigid core.

VI. CONCLUSIONS

Overall, this work proposes and tests a novel type of robotic finger pad design, where a specific type of pointed rigid internal structure with air gaps is combined with a flexible outer skin, in order to provide certain useful functionality for stable, versatile usage of the finger pad. Specifically, the designs allow objects to stably settle into the gap between adjacent points, to stably balance across two points, and also to pivot in a controlled manner across a single point. The experimental results show that the novel finger pads can successfully perform several manipulations through a wide angular range without object ejection, and that the performance is significantly better than the reference finger pad with a solid core for every object tested. The results also show some important performance effects of point spacing and different object shapes which can be used to inform future finger pad designs. Future work could analyze the different properties of the novel finger pad in more depth, or evaluate different 3D geometries for specific robotic hand designs. We hope that these results will encourage researchers to try similar finger pad structures in their own robotic hands, and to try to make more effective usage of the side surfaces of robotic fingers.

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