The Role of Digit Arrangement in Soft Robotic In-Hand Manipulation

Clark B. Teeple[1], Randall C. St. Louis[1], Moritz A. Graule[1], and Robert J. Wood[1]

***Abstract*— The need for robotic hands capable of gentle in-hand manipulation is growing rapidly as robots enter the real world. In this work, we show that the arrangement of digits in a soft robotic hand has a strong effect on in-hand manipulation capabilities. Introducing task-based performance metrics which quantify the range of motion, repeatability, and accuracy of in-hand manipulation tasks, we investigate hand designs with finger arrangements ranging from axisymmetric-circular to anthropomorphic. Using an open-source soft robot simulator, the effect of object size and aspect ratio on the in-hand manipulation performance is studied for a variety of finger arrangements, and findings are validated using a physical hardware platform. We found that the ideal finger arrangement is task-dependent; anthropomorphic arrangements excel at lateral translations, and axisymmetric arrangements are best suited for rotations. The aspect ratio of the object also has a strong effect on in-hand manipulation, with anthropomorphic designs performing best on objects of high aspect ratio, and axisymmetric arrangements doing well on objects of low aspect ratio. These findings are further confirmed in a real-world task with delicate pastries, where gentle in-hand manipulation is critical. Overall, our results suggest that active control of digit arrangement is necessary for soft robotic hands to maximize in-hand manipulation capabilities with arbitrary objects.**

I. Introduction

As robots become more integral parts of our society, we see a growing need for dexterous end effectors that are gentle and human-safe. Activities of daily living such as stocking a refrigerator, cooking food, or setting a table require human-level dexterity while maintaining gentle contact forces (typically below 10 N [1]). Collaborating with humans on tasks in the home, in the lab, or even in space requires robots to be safe by maintaining low impact energy densities [2]. Even assembly and pick-and-place tasks may require highly-dexterous end effectors when the environment is cluttered or uncontrolled. Many of these applications benefit from in-hand manipulation for fine-adjustments or additional dexterity when arms are constrained. However, designing high-dexterity robotic hands capable of high-quality in-hand manipulation is a challenging task.

Common robotic hand designs fall into two main categories: anthropomorphic and "task-driven". Human hands incorporate a combination of passive compliance and proprioception to simultaneously achieve high degrees of dexterity and gentleness, making them an excellent general-purpose design [3]. In robotics, anthropomorphic hands attempt to mimic the form of human hands, usually involving several digits arranged in a line with a single opposing 'thumb' [4], [5], [6], [7], [8]. Alternatively, "task-driven" hand designs typically descend from simpler grippers, with the goal of performing well for a specific set of tasks [9], [10], [11], [12], [13], [14]. By virtue of this "task-driven" design process, these hands have ideal dexterity for their applications, but tend to show limited performance outside of those domains.

[1]All authors with the John A. Paulson School of Engineering and Applied Sciences, Harvard University, 150 Western Ave. Boston MA 02134, USA.

This material is based upon work supported by the Wyss Institute for Biologically Inspired Engineering; the National Science Foundation (award number EFMA-1830901); a Space Technology Research Institutes grant (number 80NSSC19K1076) from NASA's Space Technology Research Grants Program; and the National Science Foundation Graduate Research Fellowship (under grant DGE1745303). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the funding organizations.

All correspondences should be addressed to Clark Teeple or Robert Wood (`cbteeple@g.harvard.edu`, `rjwood@seas.harvard.edu`)

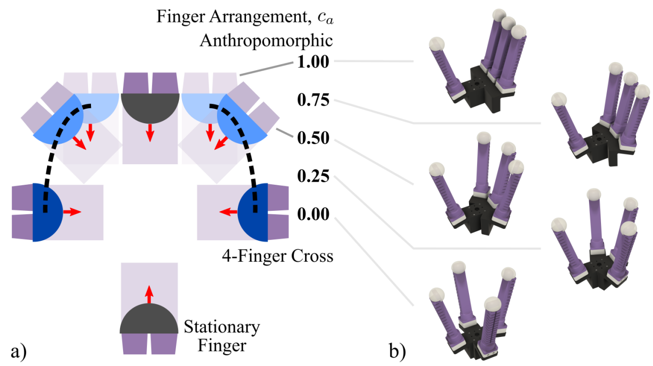

Fig. 1. In this study, we are interested in the effect of finger arrangement on in-hand manipulation capabilities. a) Based on the 2-DOF fingers from [14], we controlled the resting pose of two fingers in the hand along an ellipse to smoothly transition between "4 finger cross" and "anthropomorphic" arrangements. Using simulations and b) physical prototypes at five discrete finger arrangements, we explore the effect of finger arrangement on manipulation of a wide variety of objects.

In addition to dexterity, many of our target applications require a level of gentle interaction and safety which can most-easily be achieved using soft robots. Robots made with soft materials and structures have limited force output by design, which makes them inherently safe even in the event of a power outage or errors in control systems [15]. Over the past two decades, a large variety of soft grippers have emerged, with finger designs and digit arrangements that produce high-quality grasps in delicate situations [16], [17], [18], [19], [20]. Most of these grippers utilize several digits arranged in a radially-symmetric pattern to envelop target objects, enabling strong power grasps even in uncertain conditions. However, these soft grippers typically lack the dexterity for in-hand manipulation.

Most high-dexterity soft robotic hands use anthropomorphic finger arrangements, even though the kinematics of typical soft fingers are very different from human fingers. The RBO Hand 2 [21], BCL-13 [22], and BCL-26 [23] all use anthropomorphic finger arrangements despite also using pneumatic bending actuators as fingers. Conversely, the hand developed in [14] uses two orthogonal pairs of opposing fingers ("4-Finger Cross" arrangement), which decreases the complexity of mapping control inputs to object motions, but limits the sizes of objects that can be manipulated. All of these hands demonstrate excellent grasping and in-hand manipulation capabilities, but the question still remains: How does the arrangement of digits in a soft robotic hand affect in-hand manipulation if all other factors are identical?

II. Related Work

A small number of studies have investigated the effect of other design parameters on in-hand manipulation. In one such study, Feiz et. al found that the precision manipulation workspace of human hands becomes more restricted as the number of digits involved increases, but the range of controllable axes increases [24]. They find that using two digits for in-hand manipulation enables the largest workspace, but three digits may be more useful to ensure objects can be moved in more directions. In addition, the effect of finger design and number of degrees of freedom on dexterous manipulation has been studied [23], [25], but usually in isolation from whole-hand design.

The effect of digit arrangement on grasping has also been studied in several application-driven cases. For robotic grasping, the ability to use either an antipodal grasp (two fingers opposing) or power grasp (three or more fingers in a circle) was found to be extremely useful to expand the range of graspable object sizes and shapes [11] compared to just one of those configurations. Several commercial grippers include mechanisms to switch between these two digit configurations on the fly including the Barrett hand [9], iHY hand[11], and Robotiq 3-Finger Adaptive gripper [26]. However, these two digit configurations are designed for grasping, and may not directly transfer to in-hand manipulation. Additionally, the effect of digit arrangement on in-hand manipulation has not yet been thoroughly studied for robotic hands.

III. Designing Digit Arrangement

In this study, we employ an empirical approach to study the effects of finger arrangement on in-hand manipulation performance. Our study utilizes the dexterous soft hand platform developed in [14] which has four modular dexterous fingers, each with 2-DOF, where the finger arrangement is fully adaptable. In prior work, this hand used a "*4-finger cross*" digit configuration with fingers arranged with radial symmetry, enabling an intuitive mapping between finger control inputs and object motions. The downside of this configuration, however, is difficulty handling objects with high aspect ratios, or with dimensions larger than the hand [14]. To combat these limitations, we propose a more "*anthropomorphic*" finger configuration with three fingers arranged along a line, with a "thumb" opposing them, as shown in Figure 1. This enables cylindrical grasps of objects much longer than the hand.

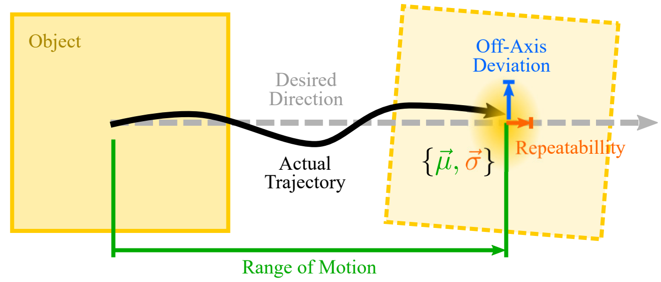

Fig. 2. We introduce three task-based performance metrics for in-hand manipulation. The *range of motion*, *repeatability*, and *off-axis deviation* measure the performance of a given motion primitive task.

For the initial design phase, we used a simulated version of the dexterous hand inside of the SoMo simulation framework [27] for quick design iterations. In simulation, we define the digit arrangement with a variable, c_a, which enables the hand to morph between the "*4-finger cross*" ($c_a = 0$) and "*anthropomorphic*" ($c_a = 1$) designs by controlling the position and orientation of the two outside fingers around an elliptical shape. Since the finger pose can be controlled directly in simulation, we enable a fine-grained evaluation of finger arrangement designs.

To validate the simulation results, we leveraged the modularity of our physical prototype hand to study five finger arrangements spanning the space from "4-finger cross" to "anthropomorphic" ($c_a = \{0.00, 0.25, 0.50, 0.75, 1.00\}$). For each finger arrangement, we designed a static scaffold to hold the fingers in the correct locations. This enables a coarser study of finger arrangements.

IV. Performance Metrics for In-Hand Manipulation

We propose a task-based approach for quantifying in-hand manipulation performance that extends beyond the typical metrics used in this space. Most performance metrics for in-hand manipulation in the literature focus on the presence or absence of finger motions or specific capabilities [3], [23] rather than on quantifying overall performance on actual tasks. Instead, we introduce a set of task-based performance metrics that do not depend upon any particular hand/finger morphology and can be easily obtained from experiments. For any given hand design, we can define a set of motion primitive tasks (moving the object) that the hand should be capable of achieving. The hand can then be commanded to perform each motion primitive task while the object's resulting motion is measured. Our performance metrics emerge from a comparison of the object's deviation from the expected trajectory over many repetitions, as shown in Figure 2.

The performance metrics introduced in this study quantify the object's motion along a desired axis as well as off-axis during a manipulation primitive. Looking in the desired axis, the *range of motion* describes the maximum position or orientation achieved by the hand, and *repeatability* describes the spread in the range of motion over multiple task repetitions. The *off-axis deviation* describes the amount of undesired motion in all other axes (L_2 norm over the other five pose dimensions normalized by the maximum translational and rotational ranges of motion). Taken together, these metrics describe how well a hand can impart a set of motion primitives onto an object, and yields a practical method to evaluate the in-hand manipulation performance of any particular hand design.

In this study, the hand prototype used is only capable of controlling object motion in the plane parallel to the palm. We can thus define three motion primitive tasks in these cardinal directions: lateral translation in the x and y-axes, and rotation about the z-axis. In addition, the hand is controlled open-loop without explicit knowledge of object properties (as discussed in the "Finger Control" section), so exact object poses are not possible to prescribe. Instead, we can re-define our motion primitive tasks to involve moving objects along desired axes (with the goal of pure motion in one axis, and zero off-axis motion). The "*range of motion*" then becomes an observed measure of the amount of motion along the desired axis rather than a measure of pose accuracy with respect to a desired object pose. This simplification enables a comprehensive study of digit arrangements without any controller design.

V. Large-Scale Design Study

We performed a large-scale design study to understand how finger arrangements affect in-hand manipulation of a variety of objects. This study is performed exhaustively in simulations, and validated with a lower resolution using our physical prototype hand. The parameter space spans six key variables, as explained in later sections:

1) **Finger arrangement,** c_a
2) **Motion primitive task**
3) Trajectory design (discussed in next section)
4) Cross-sectional shape of object (square or circular)
5) **Characteristic dimension of object's cross section**
6) **Aspect ratio of object** (perpendicular to cross section)

While finger arrangement, motion primitive task, and the object's cross sectional size and aspect ratio are primary independent variables in this study, we also know that the shape of the object and the design of the actuation signals play a large role. The shape of the object (curvature and convexity) can have a large effect on the stability of grasps even before in-hand manipulation begins [28]. In addition, the design of actuation trajectories is a critical factor in successful in-hand manipulation performance. To understand these effects, we performed a preliminary study of actuation signals before the larger design study.

A. *Finger Control and Trajectory Design*

To control the hand (in both simulation and hardware), we developed two sets of heuristic pressure trajectories: one set for each major finger arrangement, where each set enables the three critical object motion primitives. These pressure trajectories were developed for a nominal object (60 mm cube) in simulation through trial-and-error (taking actuation limits into account), and applied to the physical hand using a simple linear conversion, as discussed in [27]. The trajectories are developed for open-loop motion primitives with no aid from a perception system or any other state information. To evaluate the ranges of finger arrangements where each trajectory is valid, we performed each motion primitive study twice, applying both trajectories for every finger arrangement design.

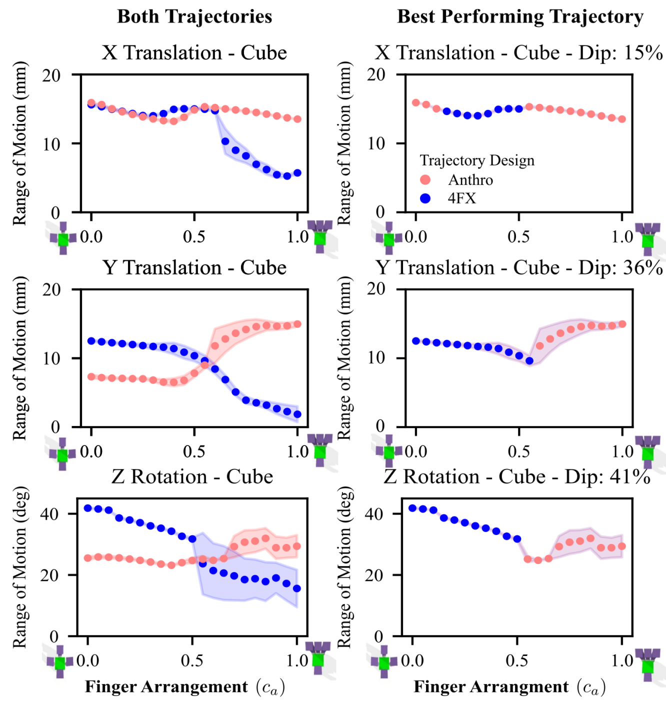

Fig. 3. The trade off in performance as a function of the trajectory design is shown for a 60 mm cube in simulation. The left columns shows the range of motion (lines) and repeatability (shaded regions around lines) of each manipulation primitive is shown with both trajectories. The right column shows the superposition of the best-performing trajectory at each finger arrangement, which exhibits only gradual degradation in the range of motion as finger arrangements move toward the $c_a = 0.5$. At worst, we lose 41% of the range of motion when performing a rotation about the z-axis at $c_a = 0.6$.

Before an exhaustive search of the parameter space, we first explored the effects of trajectory design in depth for a nominal object. As shown in Figure 3, there exists a clear trade off in performance when manipulating a 60mm cube with these two trajectory designs. Specifically, finger arrangements close to the *4-finger cross* design have higher performance when using the trajectory designed for the *4-finger cross* configuration, and vice versa for *anthropomorphic* designs. This is shown by the crossing pattern in the left column of Figure 3.

If we take the best-performing trajectory at every finger arrangement (largest range of motion), we obtain the right-column of Figure 3. These graphs show a gradual degradation in performance as each designed trajectory moves away from its reference finger arrangement, indicating that the combination of these two trajectories is robust to changes in finger arrangement. Out of the best-performing trajectories, the lowest range of motion generally occurred towards the middle of the arrangement space (near $c_a = 0.5$). For this object, the loss in range of motion due to imperfect trajectory

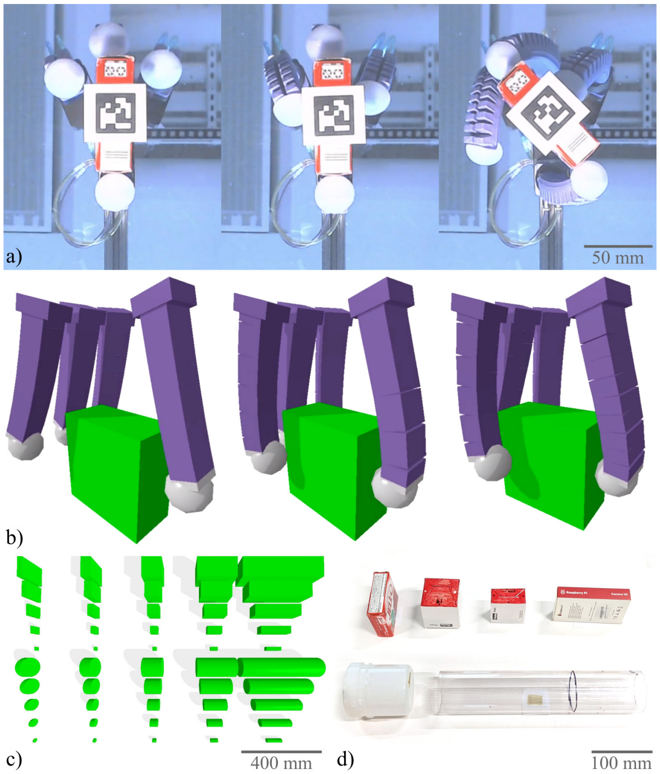

Fig. 4. Our task-based approach to evaluating in-hand manipulation starts with performing a set of primitive motions while recording the object's pose. An example of a rotation primitive performed on an object of 80 mm width and 0.5:0.5:1 aspect ratio with $c_a = 0.75$ (close to anthropomorphic) is shown a) in real hardware, and b) in simulation. c) The simulated object set consists of five widths (20 mm to 100 mm), five aspect ratios (0.25:0.25:1 to 1:1:4), and two shapes (box and cylinder). d) The real object set consists of several standard-sized everyday objects.

design is 15% for x-translation, 36% for y-translation, and 41% for z-rotation primitives. These percentages represent the percent decrease from the maximum achieved motion across the best-performing trajectory. While these performance losses are significant, we do not expect any macro-scale conclusions to be affected to a large degree by these heuristic trajectory designs.

B. Testing Procedure

The task-based performance metrics used in this study require a standardized testing procedure that works for simulations and real hardware. For a given object, finger arrangement, desired primitive motion, and trajectory design, the manipulation task is executed several times while measuring the object's 6D pose, as shown in Fig. 4. For ease of testing, objects are initially set on the ground with the hand approaching from directly above.

Simulations and real-life tests were preformed according to similar procedures, with customized steps for each. In the simulations, actuation torque signals are applied to the fingers while object's pose is logged, enabling performance metrics to be calculated directly from the data. However, a few simulations became numerically unstable; these points were excluded from the results. For real-life experiments, actuation signals are converted to actuation pressure signals and executed with a real-time pressure controller [29] (same as in [14]). In addition, objects are fitted with April Tags [30] for pose tracking, and manipulated on a clear acrylic table with a camera viewing the scene from below. All real hardware experiments are controlled using Robot Operating System (ROS, [31]), and performance metrics are calculated using the pose estimates.

C. Object Set

To test the effects of the size and aspect ratio of target objects on in-hand manipulation, we chose a suitable set of simple objects which span this space. For the simulations, we used a procedurally-generated set of geometrically simple objects, where we control the cross-sectional size and the aspect ratio with only two unique parameters. We chose two basic geometric primitives (cylinders and boxes), five cross-sectional widths ranging from 20 mm (fingertip diameter) to 100 mm (largest object to fit inside the resting hand), and five aspect ratios ranging from 0.25:0.25:1 to 1:1:4. Overall, $2 \times 5 \times 5 = 50$ simulated objects were generated using this discretization, as shown in Figure 4c.

For real-world testing, we used a sparser set of everyday objects and food items. To validate our simulation results, we used a combination of packing boxes for various retail items (raspberry pi camera, jello, and pneumatic connectors), and also a plastic jar and tube. These objects roughly span the space of sizes and aspect ratios of the simulations (as shown in Figure 4d). Finally, in a real-world demonstration, we used two delicate pastries (sweet bun and cupcake) as shown in Figure 7.

Several object properties were ignored in this study, but remain important for future explorations. Since we are interested in the geometric properties of hand design, the mass and mass distributions of objects were not varied, however the mass of objects can drastically affect real-world tasks. In simulations, all objects had a constant mass of 0.010 kg to minimize friction effects with the ground. We also designed the fingers to ensure that friction is high between the fingertips and the object, and chose testing surfaces to ensure sufficiently low friction between the object and the ground. Rolling contact between the fingertips and the object (forces always within the friction cone) during in-hand manipulation is also assumed, though not always true. While these simplifications restrict our testing environment, we do not expect them to affect our conclusions.

VI. Results

Based on our experiments, we find that the finger arrangement of a soft hand affects not only the in-hand manipulation performance as a function of object sizes and aspect ratios, but also the overall success of motion primitive tasks. These results are summarized in Figures 5 and 6.

To obtain relevant slices of the 6D parameter space, the data is condensed by taking averages or maximums over some of the dimensions. Since two trajectory designs were tested for each experiment, we can collapse this dimension by taking the best-performing result (largest range of motion)

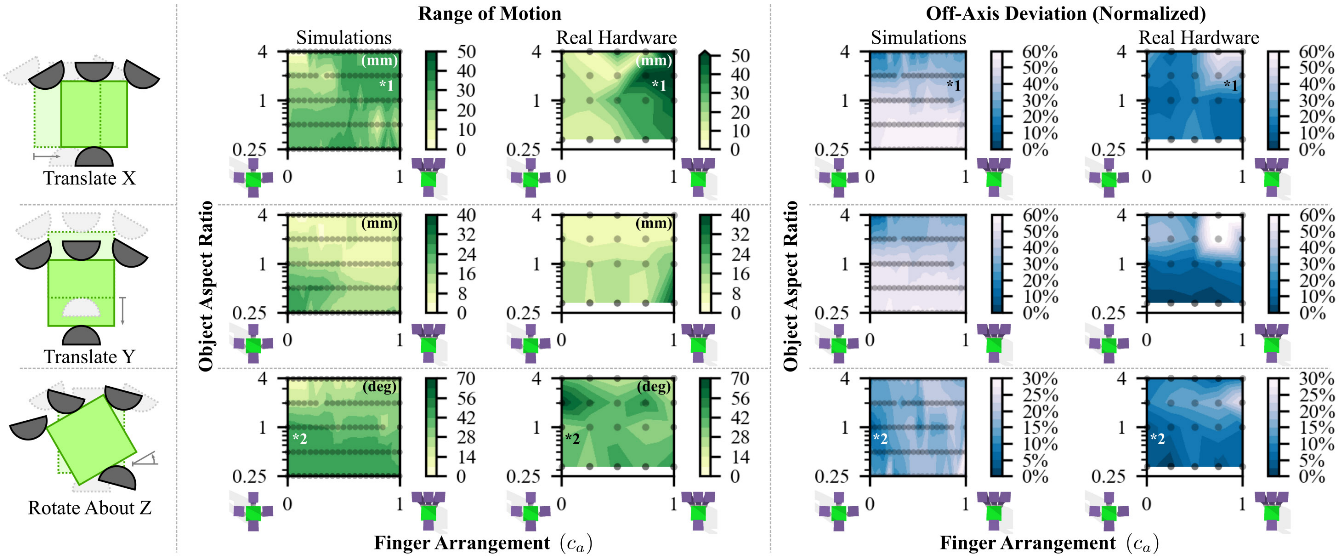

Fig. 5. Each of the three motion primitive tasks is best-performed with different finger arrangements. Overall, "anthropomorphic" finger arrangements ($c_a = 0.75$–1.0) are good at performing translations in the x-direction, with a 30-50 mm range of motion, marked by "*1" in the plots. The "4-finger cross" arrangements ($c_a = 0.0$–0.25) are excellent at rotations about the z-axis, with 40-70° range of motion and 10-20 % off-axis deviations, marked by "*2" in the plots. All finger arrangements struggled with y-translation of high-aspect ratio objects (above 2.0). All of these trends appear in real hardware and simulations, with reasonable agreement between the two for x-translation and z-rotation. Points on plots represent values of parameter space tested. Each point is an average over $n = 10$ trials in simulation, and $n = 4$ trials for real experiments. Contours are linear interpolations.

at each point. Additionally, in the simulations, we took the mean value over the two object shapes (box and cylinder), but the physical tests only report results from boxes since the boxes spanned the entire space of aspect ratios. From here, slices of the parameter space are taken at relevant values of the object's size and aspect ratio.

Figure 5 shows that each of the three motion primitive tasks is best-performed within separate ranges of finger arrangements. Taking a slice through the parameter space at mid-sized objects (60 mm), we see that "anthropomorphic" finger arrangements ($c_a = 0.75$–1.0) can perform high quality translations of high-aspect ratio objects in the x-direction, with a large range of motion (30-50 mm), but also large off-axis deviations (~ 40 %). Conversely, the "4-finger cross" arrangements ($c_a = 0.0$–0.25) are excellent at rotations about the z-axis, with large range of motion (40-70°) and small off-axis deviations (10-20 %). All finger arrangements struggled with y-translation of high-aspect ratio objects (above 2.0) with less than 16 mm of motion. These results are summarized in Table I. Overall, we see the same large-scale trends in real hardware and simulations, with the range of motions matching well. However, the off-axis deviation for translational motions have opposite trends in hardware compared to simulations, likely due to limitations of the modeling framework when implementing high-friction fingertip surfaces.

Figure 6 shows that in-hand manipulation performance of each major family of finger arrangements is tied directly to the aspect ratio of the object. Taking an average over all primitive motions (with ranges of motion normalized by the maximum values for each primitive), we can see that the "4-finger cross" arrangement ($c_a = 0.0$–0.25) and even the

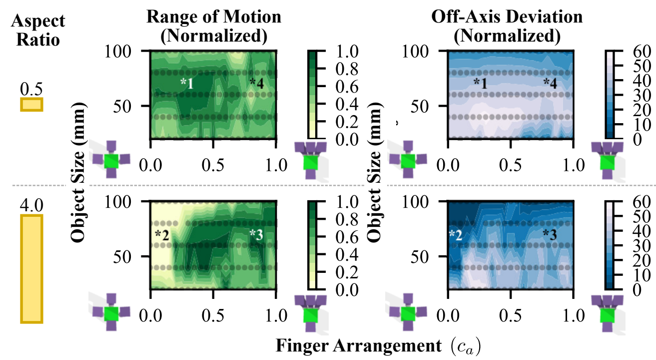

Fig. 6. Object aspect ratio directly affects in-hand manipulation performance for all motion primitives. "4-finger cross" finger arrangements excel at manipulating larger objects with small aspect ratios (indicated by "*1" in the plots), and have extreme difficulty with high-aspect ratio objects ("*2"). Anthropomorphic finger arrangements perform well with high aspect ratio objects regardless of size ("*3"), but do poorly with objects of lower aspect ratio, ("*4"). Points on the plots represent values in the parameter space tested. Each point is an average over $n = 10$ trials in simulation. Contours are linear interpolations.

intermediate arrangements ($c_a = 0.25$–0.6) successfully manipulate large, thin objects. For an aspect ratio of 0.5, the "4-finger cross" has a large range of motion (80% of maximum) with moderate off-axis deviation (20-30 %) for objects larger than 50 mm. In addition, the "4-finger cross" arrangements produce extremely poor performance with high-aspect ratio objects (essentially no motion produced). On the other hand, "anthropomorphic" finger arrangements ($c_a = 0.75$–1.0) perform well (50-100% of maximum range of motion) with high aspect ratio objects regardless of size, but do poorly (20-40% of maximum range of motion) with objects of lower aspect ratio. Lastly, there appears to be a local performance

TABLE I

OVERALL PERFORMANCE FOR EACH MOTION PRIMITIVE

	Max Range of Motion			Max Off-Axis Dev.		
Finger Arr.	**x-tran**	**y-tran**	**z-rot**	**x-tran**	**y-tran**	**z-rot**
4-Finger X	20 mm	**24 mm**	70°	**25%**	**40%**	**20%**
Anthro.	**50 mm**	12 mm	45°	40%	60%	30%

* Best-performing finger arrangements are marked in **bold**.

TABLE II

OVERALL PERFORMANCE AS A FUNCTION OF OBJECT ASPECT RATIO

	Max Range of Motion		Max Off-Axis Dev.	
Finger Arr.	**aspect: 0.5**	**4.0**	**0.5**	**4.0**
4-Finger X	**80%**	0%	**30%**	60%
$c_a = 0.50$	**80%**	**100%**	60%	40%
Anthro.	40%	**100%**	40%	**30%**

* Best-performing finger arrangements are marked in **bold**.

maximum for finger arrangements between $c_a = 0.25$ and $c_a = 0.5$, with good performance (above 60% of maximum range of motion) over both aspect ratios. These results are summarized in Table II.

Finally, while repeatability was evaluated, no significant trends existed. In the physical experiments, the standard deviation of the amplitude of motions never exceeded 24% of the maximum range of motion for over all primitive motions, and the simulations yielded a standard deviation of at most 28% of the maximum range of motion. This larger variance in the motion of objects is likely due to variation in friction forces with the ground as well as slippage between the fingertips and the object.

VII. TRANSLATION TO REAL-WORLD TASKS

The results from our study with simple objects and simple motion primitives can be extended to pick-and-place operations on delicate real-world objects. In Figure 7, two different finger arrangements are required to effectively perform fine pose adjustments on two pastries with different aspect ratios (sweet bun and cupcake). For each of the two major finger arrangements, we attempt to translate the bun in the x-direction before releasing, and rotate the cupcake about its z-axis to reveal a fiducial marker. For these demonstrations, the hand is fixed to a UR5e 6-DOF robot arm (Universal Robots), and poses are heuristically-designed without the aid of a perception system. The hand and robot are coordinated using ROS [31].

To translate the high-aspect ratio sweet bun (1:1:3.3, 30 mm×30 mm×100 mm) in the x-direction, the "anthropomorphic" finger arrangement performs best, translating the bun without damage. However, the "4-finger cross" finger arrangement damaged the bun (applied a large stress from the fingertip) while grasping due to limitations in the maximum dimension that can fit within the fingers when retracted. The bun was damaged further when attempting to perform the translation primitive. These results are expected given the trends we see in our design study.

To rotate the cupcake (aspect ratio of 1:1:1, 50 mm×50 mm×50 mm) about its z-axis, the "4-finger cross" arrangement performs best, with a stable grasp and stable, consistent, well-controlled rotation within the hand. However, the "anthropomorphic" arrangement is unable to perform a stable grasp without a large (60 deg.) initial rotation, and rotation primitives had much larger off-axis motion during the motion. These observations also match the results of the design study.

VIII. DISCUSSION

The trends presented in the design study and real-world demonstrations can be explained by a simple analysis of geometry and grasping forces. Based on this analysis, we extract several design rules for high-performance in-hand manipulation using soft hands. Our results also suggest that on-the-fly control of digit arrangement would enable a robot to maximize in-hand manipulation performance with arbitrary objects. These results can then be extended to other finger designs, actuation mechanisms, and combinations of degrees of freedom.

A. Geometry Explains Performance Differences Between Digit Arrangements

Static grasp stability can be used to explain why certain finger arrangements are better suited for specific tasks. When grasping, the "4-finger cross" arrangements apply contact forces to the object in an axisymmetric way, thus excelling at axisymmetric motion primitives such as z-axis rotations. Conversely, the "anthropomorphic" arrangements apply contact forces to the object with several fingers on one side balanced by an opposing thumb, leading to high-quality linear motion primitives.

A simple analysis of geometric features of each finger arrangement can help explain the strong effect of object aspect ratio on in-hand manipulation performance over all motion primitive tasks. While all finger arrangements have practical size limits on grasp-able objects, "anthropomorphic" finger arrangements have an effectively infinite size range parallel to the direction of the fingers. This liberates "anthropomorphic" hands to grasp high-aspect ratio objects with ease, and in-hand manipulation performance is high as a consequence. However, the opposing nature of the forces produced during grasping make stabilizing objects with smaller aspect ratios challenging for "anthropomorphic" hands. Conversely, "4-finger cross" arrangements have object size limits in all directions, making it difficult to grasp high aspect ratio objects (and thus difficult to manipulate), but enabling more-stable grasps on low-aspect ratio objects.

This simple analysis reveals an important result: to maximize open-loop in-hand manipulation performance for a large variety of objects and tasks, active control of digit arrangement is necessary. Achieving the best of both worlds without additional control or planning can be achieved if a hand can adapt between these two finger arrangements with a 1-DOF mechanism. This result is consistent with findings in previous studies on hand design for grasping, where a 1-DOF mechanism is sufficient to achieve precision and power grasping [11].

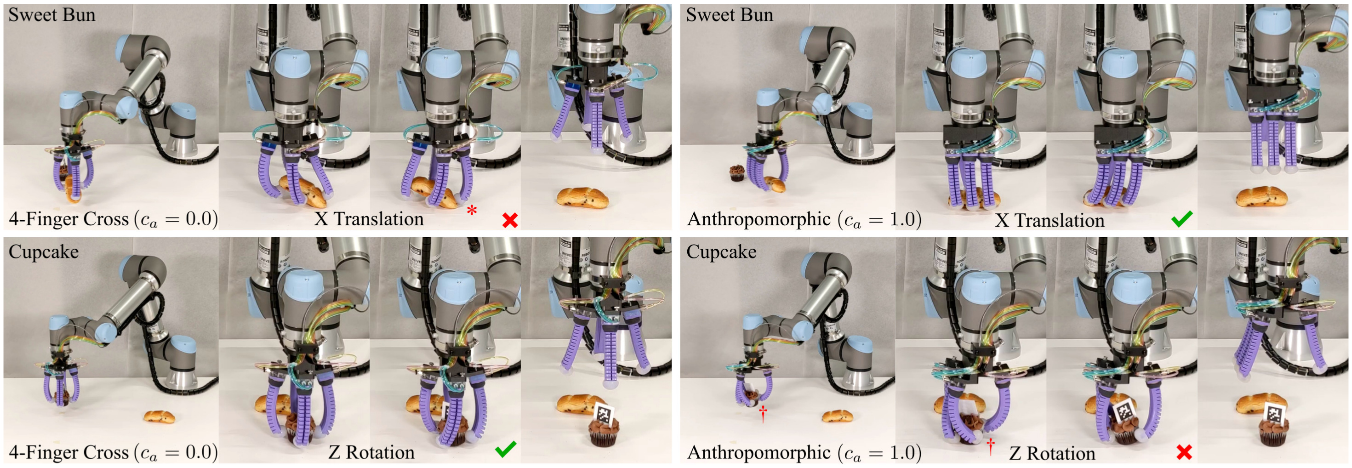

Fig. 7. When manipulating two delicate pastries, two different finger arrangements are required to effectively perform fine pose adjustments. Due to the high aspect ratio of the sweet bun, the "anthropomorphic" finger arrangement performs the best translation in the X-direction, with the "4-finger cross" arrangement damaging the bun (marked with "*"). Similarly, due to the lower aspect ratio of the cupcake, the "4-finger cross" arrangement performs the most-effective rotation about the z-axis, with the "anthropomorphic" arrangement inducing large off-axis motion (marked with "†").

B. *Successful Digit Arrangements Depend on Finger Design*

In all of these results, passive compliance plays a primary role in enabling successful in-hand manipulation. Bending compliance in the fingers is responsible for the ability to grasp and manipulate a wide range of object sizes without explicit knowledge of any properties of objects. Additional compliance in the fingertips helps ensure stability while manipulating objects due to the large, high-friction contact areas. Compliance also limits contact pressure on delicate objects (such as pastries) by ensuring contact forces are small and distributed over large areas.

Finally, some of the motion primitives included in this study are only possible due to the 2-DOF finger design we used. If 1-DOF fingers were used (where only the primary bending axis is controlled), then the "anthropomorphic" finger arrangement could not perform controlled x-translations since the fingertips only point in the y-direction. Similarly, the "4-finger cross" arrangement could not perform controlled z-rotations, as the fingers only point toward the center of the object. The 2-DOF fingers used in this study were specifically designed to combat these potential limitations, but the total number of controlled degrees of freedom could potentially be reduced in future iterations (i.e., mixing "simple" and "dexterous" fingers together in one hand).

C. *Limitations*

A number of design decisions limit the scope of the results presented above. The biggest limitation is that all in-hand manipulation in this study was performed open-loop, and is highly-dependent on the exact finger trajectories used. Trajectories were designed specifically for the two major finger arrangements tested, but not for any intermediate finger arrangements. Without any knowledge of object sizes, on-board sensing in the fingers, or modeling, the performance of finger arrangements in the middle of the scale (near $c_a = 0.5$) could potentially be improved if trajectories were specifically designed for each finger arrangement. Furthermore, if a modeling framework were implemented, finger input trajectories could then be planned directly rather than designed by a human. Given a motion planning system for the fingers, we would expect overall improved performance, but the trends seen in our study would likely still hold.

The other main limitation of this study is our choice of the two main finger arrangements. These two arrangements are an excellent starting point, but this study does not involve any first-principles analysis or design. A physics-based analysis of the in-hand manipulation problem could yield a superior finger arrangement that falls outside of these two specific designs (for example, different number of digits, different mounting angles, etc). However, we believe the conclusions drawn in this study would still apply to finger designs falling within the two families of designs studied (anthropomorphic and axisymmetric).

IX. Conclusions

In summary, we demonstrated that in-hand manipulation performance is directly tied to the arrangement of digits in a soft robotic hand, and that on-the-fly control of digit arrangement is necessary to achieve the best performance for arbitrary objects. Through a large-scale design study, we found that certain motion primitives are best-accomplished with different ranges of finger arrangements, with "anthropomorphic" arrangements performing well with x-translations, and "4-finger cross" arrangements excelling with z-rotations. We also found that the aspect ratio of the object affects in-hand manipulation performance over all motion primitive tasks, where high aspect ratio objects are best-handled with anthropomorphic designs, and "4-finger cross" arrangements performing better with low aspect ratio objects. Finally, we demonstrated that these findings extend to a real-world manipulation task where gentle in-hand manipulation is desired.

In future work, we plan to develop a soft robotic hand with one additional degree of freedom to control the digit arrangement on-the-fly. We are also interested in developing a modeling and motion planning framework for soft fingers to directly plan finger motion to achieve desired object motions. Given such a modeling framework, new finger arrangements could be explored beyond those a human designer can manifest. Another additional avenue would be to explore how to distribute the total number of controlled degrees of freedom such that we maximize the benefits of passive compliance while still enabling useful in-hand manipulation. Finally, integrating soft dexterous hands into more real-world testing scenarios will help push forward the development of safe, highly-capable soft hands suitable for real applications in human-centric environments.

ACKNOWLEDGEMENTS

The authors thank Grace Kim, Daniel Bruder, and Thomas McCarthy for valuable discussions during simulation development.

REFERENCES

[1] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *Journal of neuroengineering and rehabilitation*, vol. 11, no. 1, pp. 1–29, 2014.

[2] S. Robla-Gómez, V. M. Becerra, J. R. Llata, E. Gonzalez-Sarabia, C. Torre-Ferrero, and J. Perez-Oria, "Working together: A review on safe human-robot collaboration in industrial environments," *IEEE Access*, vol. 5, pp. 26 754–26 773, 2017.

[3] J. Zhou, Y. Chen, D. C. F. Li, Y. Gao, Y. Li, S. S. Cheng, F. Chen, and Y. Liu, "50 benchmarks for anthropomorphic hand function-based dexterity classification and kinematics-based hand design," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2020, pp. 9159–9165.

[4] L. B. Bridgwater, C. Ihrke, M. A. Diftler, M. E. Abdallah, N. A. Radford, J. Rogers, S. Yayathi, R. S. Askew, and D. M. Linn, "The robonaut 2 hand-designed to do work with tools," in *2012 IEEE International Conference on Robotics and Automation*. IEEE, 2012, pp. 3425–3430.

[5] A. Kochan, "Shadow delivers first hand," *Industrial robot: an international journal*, vol. 32, no. 1, pp. 15–16, 2005.

[6] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive synergies for the design and control of the pisa/iit softhand," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 768–782, 2014.

[7] J.-H. Bae, S.-W. Park, J.-H. Park, M.-H. Baeg, D. Kim, and S.-R. Oh, "Development of a low cost anthropomorphic robot hand with high capability," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012, pp. 4776–4782.

[8] L. Tian, H. Li, Q. Wang, X. Du, J. Tao, J. S. Chong, N. M. Thalmann, and J. Zheng, "Towards complex and continuous manipulation: A gesture based anthropomorphic robotic hand design," *arXiv preprint arXiv:2012.10981*, 2020.

[9] W. Townsend, "The barretthand grasper–programmably flexible part handling and assembly," *Industrial Robot: an international journal*, vol. 27, no. 3, pp. 181–188, 2000.

[10] R. R. Ma and A. M. Dollar, "An underactuated hand for efficient finger-gaiting-based dexterous manipulation," in *2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014)*. IEEE, Dec 2014, p. 2214–2219.

[11] L. U. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, "A compliant, underactuated hand for robust manipulation," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, 2014.

[12] J. Zhou, S. Chen, and Z. Wang, "A soft-robotic gripper with enhanced object adaptation and grasping reliability," *IEEE Robotics and Automation Letters*, vol. 2, no. 4, pp. 2287–2293, Oct 2017.

[13] W. Friedl, H. Höppner, F. Schmidt, M. A. Roa, and M. Grebenstein, "Clash: Compliant low cost antagonistic servo hands," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2018, pp. 6469–6476.

[14] S. Abondance, C. B. Teeple, and R. J. Wood, "A dexterous soft robotic hand for delicate in-hand manipulation," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 5502–5509, 2020.

[15] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, p. 467, 2015.

[16] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft robotic grippers," *Advanced Materials*, p. 1707035, 2018.

[17] R. Deimel and O. Brock, "A compliant hand based on a novel pneumatic actuator," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 2047–2053.

[18] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, and D. F. Gruber, "Soft Robotic Grippers for Biological Sampling on Deep Reefs," *Soft Robotics*, vol. 3, no. 1, p. soro.2015.0019, 2016.

[19] C. B. Teeple, T. N. Koutros, M. A. Graule, and R. J. Wood, "Multi-segment soft robotic fingers enable robust precision grasping," *International Journal of Robotics Research*, 2020.

[20] N. R. Sinatra, C. B. Teeple, D. M. Vogt, K. K. Parker, D. F. Gruber, and R. J. Wood, "Ultragentle manipulation of delicate structures using a soft robotic gripper," *Science Robotics*, vol. 4, no. 33, 2019.

[21] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 161–185, 2016.

[22] J. Zhou, J. Yi, X. Chen, Z. Liu, and Z. Wang, "Bcl-13: A 13-dof soft robotic hand for dexterous grasping and in-hand manipulation," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 3379–3386, 2018.

[23] J. Zhou, X. Chen, U. Chang, J.-T. Lu, C. C. Y. Leung, Y. Chen, Y. Hu, and Z. Wang, "A soft-robotic approach to anthropomorphic robotic hand dexterity," *IEEE Access*, vol. 7, p. 101483–101495, 2019.

[24] T. Feix, I. Bullock, Y. Gloumakov, and A. Dollar, "Effect of number of digits on human precision manipulation workspaces," *IEEE Transactions on Haptics*, 2020.

[25] M. Liarokapis and A. M. Dollar, "Deriving dexterous, in-hand manipulation primitives for adaptive robot hands," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2017, pp. 1951–1958.

[26] Robotiq, "3-finger adaptive robot gripper," *Online datasheet*, 2021. [Online]. Available: https://robotiq.com/products/3-finger-adaptive-robot-gripper

[27] M. A. Graule, C. B. Teeple, T. P. McCarthy, R. C. St. Louis, G. R. Kim, and R. J. Wood, "Somo: Fast and accurate simulation of continuum robots in complex environments," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021.

[28] M. R. Cutkosky and P. K. Wright, "Friction, Stability and the Design of Robotic Fingers," *The International Journal of Robotics Research*, vol. 5, no. 4, pp. 20–37, 1986.

[29] C. B. Teeple, "Ctrl-p, v2.0," *Computer Software*, Feb. 2020. [Online]. Available: https://github.com/cbteeple/pressure_controller

[30] J. Wang and E. Olson, "AprilTag 2: Efficient and robust fiducial detection," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, oct 2016, pp. 4193–4198.

[31] M. Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: an open-source robot operating system," in *ICRA Workshop on Open Source Software*, 2009.