Comparison and Analysis of Two, Three and Four Fingered Soft Pneumatic Grippers for the Purpose of Grasping and Lifting Objects of Various Morphology

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***Abstract*—This study aims to identify the optimal number of fingers for silicon-moulded pneumatic grippers tasked with grasping and lifting a variety of standard shapes. Grippers with two, three and four fingers are fabricated and their performance is compared in grasping and lifting a sphere, cube, cuboid and cone. The three-fingered gripper, designed asymmetrically to immitate the morphology of natural grasping mechanisms found in birds of prey, performed best with a success rate of 95% across all trials. Using the experimental results and current literature, an improved gripper design for future studies is presented. Design files are publicly available on the author's GitHub for researchers to access: https://github.com/Hinlo/Comparison_of_Soft_Pneumatic_Grippers**

***Index Terms*—Soft, Pneumatic, Gripper, Grasping, Bio-inspired, Robotics.**

I. INTRODUCTION

Soft robotics is a growing field which finds applications from inconspicuous monitoring of marine life [1] to the actuation of haptic feedback for prosthesis, sensory substitution or remote social touch [2][3], among many others. These contrasting examples demonstrate that researchers across all genres of Robotics have taken note of recent advances in soft technology and are investigating their uses. Pneumatic grippers, able to deform to grip objects with varied and irregular morphologies, have seen rapid uptake in the harvesting of delicate produce such as fruits [4].

The question of optimal structure for pneumatic grippers remains unanswered, however. Different topologies can provide different grasping types. While most grippers fully enclose objects with uniform curvature, *Liu S et al.* [5] added a soft joint creating two separately pressurised chambers in each gripper finger. This results in a "pinch" style vertical grasp which may be advantageous for a firm grasp of very small objects; just as humans may use a pinch to grasp smaller objects.

Specifically, the optimal number of gripping fingers has not been discerned. *Liu C et al.* [6] found, for two and three-fingered grippers with identical topology, pressurised to $80kPa$, a maximum payload of 2.66kg and 5.12kg respectively. This result suggests that at a fixed pressure a three-fingered gripper is superior, nearly doubling the lifting capacity. A four-fingered gripper has been considered by *Salem et al.* [7] which, via direct 3D printing as opposed to mould-casting, can be operated at pressures up to $500kPa$, though no maximum payload is given. Connecting these fingers to a rotating soft wrist, the researchers state that orientation can be varied to lift a wider range of objects, though the wrist has not been verified experimentally.

Image processing allows us to quantitatively compare the performance of different grippers. This is demonstrated by *Le et al.* [8] who compared the bending angle of grippers with differing chamber wall thickness at the same pressure in Abaqus and MATLAB simulation and experimentally; via image processing in MATLAB. They found that both simulations overestimated the curvature of the $1.5mm$ thick chamber gripper and underestimated the curvature of the $2.5mm$ thick gripper. This indicates that image processing on experimental performance is likely more useful than predicting performance via simulation given that most soft grippers are simple and inexpensive to fabricate via casting, so casting multiple iterations is not an issue. In addition to angle curvature, image processing can display the level of contact between the gripper and the object, providing insight into the security of the grasp.

II. DESIGN & METHODS

Fig. 1 displays the three grippers fabricated and compared in this project. Each gripper is pressurised via a fixed volume $60cm^3$ syringe of air, attached to the gripper tubing. The two-fingered gripper was fabricated first and tested on a variety of objects. These preliminary trials demonstrated that, while versatile, the gripper performed better at different orientations on different objects. Based on this finding, the

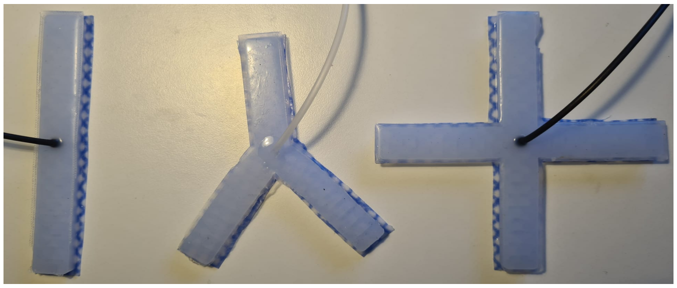
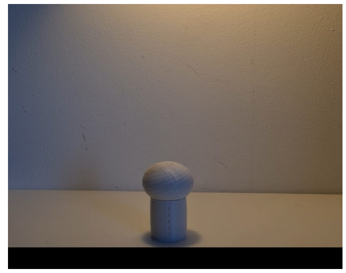


Fig. 1. The three grippers fabricated in this project. Each with identical internal structure. The two and four-fingered grippers have rotational symmetry of orders two and four respectively. The three-fingered gripper is asymmetrical, with $90°$ between two lower fingers as pictured and $135°$ between those two and the third finger.

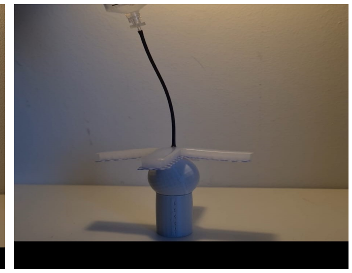
three and four-fingered gripper moulds were designed in Fusion 360 [9] and the grippers fabricated. These grippers were templated from the two-fingered gripper to ensure an identical internal structure. The three-fingered gripper was designed asymmetrically, inspired by the grasping abilities of birds of prey [10], which typically have one toe pointed backwards at an obtuse angle to the others. Prototypes of these grippers had issues with bursting at the constraining layer seal when under pressure. This was mitigated in the final versions by adding a second layer of silicon at the seal points on each gripper once it had fully set.

Having fabricated each gripper, the following hypothesis is stated:
Due to their increased number of fingers, the three and four-fingered grippers will be more robust to changes in grasping orientation for different objects and thus will outperform the two-fingered gripper experimentally.

Fig. 2 shows the experimental procedure for each trial. For each gripper, five repeated trials attempting to grasp and lift each shape were performed. The shapes were set on a raised platform. The shapes had the following dimensions; sphere of radius $15mm$ and mass 8g, cone of height $30mm$, face radius $20mm$ and mass 9g with point facing upward, cube of side length $30mm$ and mass 14g, cuboid with side lengths $30 \times 30 \times 60mm$ and mass 26g oriented with long face horizontal. The platform is a hollow cylinder with height $30mm$, face radius of $14mm$. Elevating shapes with the platform allows superior grasping around the whole object. Each gripper is lowered vertically to rest on the shape without manually setting the orientation of contact. $60cm^3$ of air is supplied to pressurise each gripper, the maximum amount which the syringe can supply. Once the gripper is fully pressurised, it is lifted by the syringe. If the shape is grasped and lifted off the platform for more than 5 seconds, the trial is considered a success. If the shape is not lifted or is dropped within 5 seconds, it is considered a failed trial.

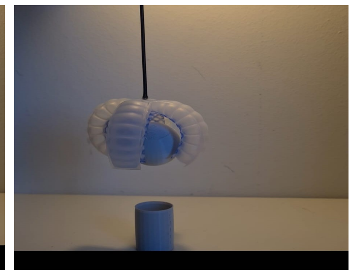


(a) Shape on Platform

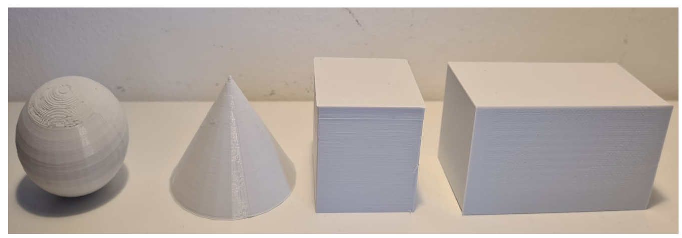


(b) Gripper Lowered onto Shape

(c) Gripper Pressurised to Grasp



(d) Gripper Lifted



(e) The Four Standard Shapes Used in Trials

Fig. 2. Experimental Procedure. Each shape is placed on a hollow cylindrical platform, the gripper is lowered freely to make contact, pressurised to grasp and lifted as shown in images (a) to (d). (e) displays the Sphere, Cone, Cube and Cuboid used in the trials, in the orientation in which they were placed on the platform.

III. Results & Analysis

Results are displayed in Fig. 3. As trial results are binary (successful or unsuccessful), uncertainties and therefore statistical significance between the three grippers cannot be determined. Yet results indicate that, with the volume of air supplied, the three-fingered gripper is the most reliable and versatile. This is likely due to reasonably high pressure and improved morphology taking inspiration from natural avian grasping. The two and four-fingered grippers each performed well in particular shapes; the cube and cuboid respectively. This demonstrates their utility for grasping certain objects.

Qualitatively, the two-fingered gripper was able to near-fully enclose the smaller sphere and cube from any orientation, leading to good performance. Comparatively, it was unable to enclose the cuboid if its fingers were parallel with the long edge and could not reach fully under the cone to grip the flat face. In comparison, the three-fingered gripper was much more resilient to changes in orientation, resulting in more consistently successful trials. In particular, with the

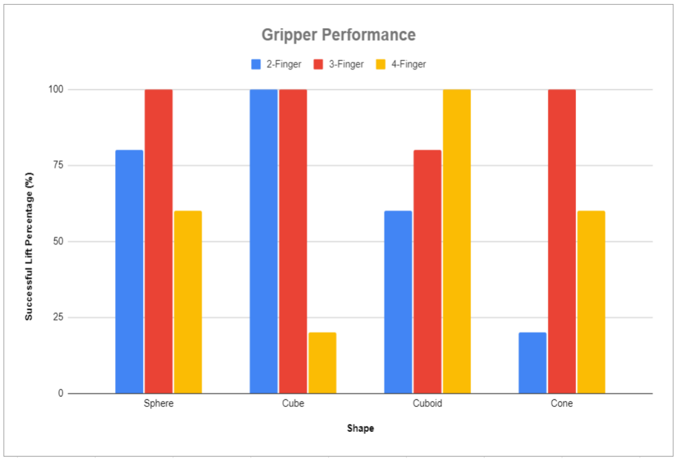


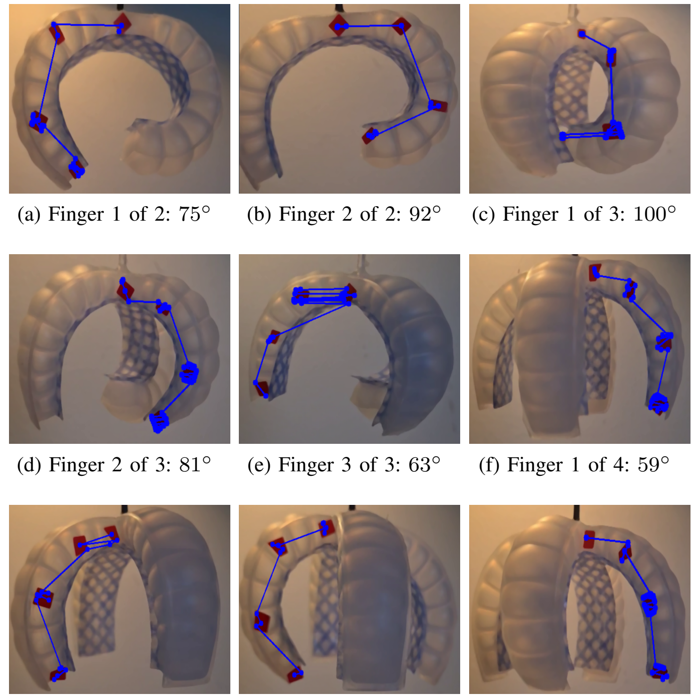
Fig. 3. Averages: 2-finger 65% success, 3-finger 95% success, 4-finger 60% success - across 5 trials per gripper per shape.

cone, the asymmetrical design allowed the two close fingers to lift from underneath on the flat face while the third finger secured the cone on the curved surface. The four-fingered gripper did not achieve enough pressure with the limited air supply to fully enclose the sphere, cube and cone, resulting in inconsistent performance. The cuboid, being significantly larger, required less inflation to fully enclose and as a result, the four-fingered gripper with its high rotational symmetry was successful in each trial.

As each gripper contains a different volume of internal pneumatic chambers, when inflated, the two-fingered gripper will reach the greatest pressure, while the four-fingered gripper reaches the lowest pressure. Due to limited access to pneumatic pressure sensors, only the 3-fingered gripper was tested, averaging $126.85 \pm 0.07\ kPa$ across three measurements.

Considering Fig. 4, the angle of curvature achieved by each arm of each gripper provides insight into the reason behind the results seen in Fig. 3. Angles were taken using digital measurement with the images displayed in Fig. 4.

The curvature of each arm of the two-fingered gripper is significantly different. This aids in explaining further why this gripper's performance was highly dependent on contact orientation with the object. While the design indicates a rotational symmetry of order two, experimentally the gripping angle of each arm differs by 17° and thus the gripper orientation does not have any real-world rotational symmetry. This did not matter as much on the cube, which was enclosed by each finger successfully. But on the cone, the 92° curve was too extreme to grasp the flat bottom face and unlike the other grippers, the two-fingered gripper cannot enclose objects laterally as well as vertically. This meant that the cone often slipped out of the grasp of this gripper, leading to a success rate of only 20%.



(a) Finger 1 of 2: 75° (b) Finger 2 of 2: 92° (c) Finger 1 of 3: 100°
(d) Finger 2 of 3: 81° (e) Finger 3 of 3: 63° (f) Finger 1 of 4: 59°
(g) Finger 2 of 4: 63° (h) Finger 3 of 4: 72° (i) Finger 4 of 4: 59°

Fig. 4. Each finger of each gripper, inflated with $60cm^3$ of air via pneumatic syringe. Images (a) and (b) are the two-fingered gripper, (c)-(e) are the three-fingered gripper and (f)-(i) are the four-fingered gripper. Grasping angles are measured from the horizontal at the point where curvature begins on the constraining layer. Due to the warm lighting and large colour pads, thresholding issues occurred, most apparent in image (e). This was rectified as far as possible and does not affect angle measurements.

The large curvature of the two close fingers on the three-fingered gripper provides evidence for its strong performance on the sphere. the constraining layer is $54mm$ in length and does not expand, thus forming an arc, S, when pressurised, which we will assume has uniform curvature. the Curvature angle of $\theta = 100°$ from the horizontal therefore allows the calculation of the radius of the arc formed by finger 1 of 3. The circumference of the circle formed by the arc is found using the angle of curvature from the vertical, $\theta_{vert} = 100° + 90° = 190°$. Circumference, c, is then given by:

$$S = 54mm = \frac{c}{2} \times \frac{190}{180}$$

, rearranged:

$$c = \frac{2 \times 54 \times 180}{190} = 100mm\ (2sf)$$

radius is then given by $r = \frac{c}{2\pi} = 16mm\ (2sf)$ This calculation shows that r is very near $15mm$, the radius of the sphere, which is why the three-fingered gripper demonstrated such a secure grasp of the sphere in particular; the contact between this finger and the sphere is nearly a perfect fit. This is modelled in Fig. 5. Other shapes could not be compared quantitatively in this way as the cube and cuboid have no

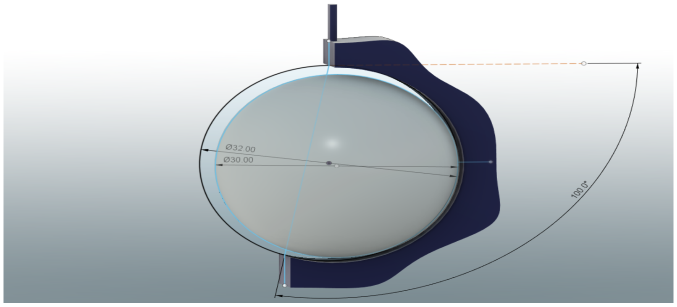


Fig. 5. A model of finger 1 of the three-fingered gripper, creating an arc with radius $16mm$ which tightly encloses the sphere of radius $15mm$.

curvature and the cone's plane of curvature is orthogonal to the curvature of the gripper fingers. The disparity in each finger's angle of curvature, while the largest of the three grippers at 37°, does not significantly impact performance due to intelligent morphology which encourages secure grasping.

The lower average curvature angles achieved by the four-fingered gripper are evidence of the lower pressure in this gripper due to the limited air supply and greater volume of chambers to pressurise. This supports the comparatively poor experimental performance of this gripper. Besides the large cuboid, the curvature angle and pressure achieved by this gripper were not enough to consistently enclose and lift the shapes. For example, the gripper successfully lifted the cube when the fingers lined up with the vertical edges of the cube, as opposed to lining up with the vertical faces, as the edges provide more pronounced contact and friction. The finger curvature angles are however much more consistent than the other two grippers, with a range of only $13°$ between the minimum and maximum angles.

Overall, the results shown in Fig. 3 show that the hypothesis stated in section II is true for the three-fingered gripper, with an average percentage success rate of 95% across all trials compared to the two-fingered gripper at 65%. With the volume of pressurising air limited to $60cm^3$, the hypothesis is invalid for the four-fingered gripper which achieved an average success rate of only 60%. It is expected that in an experiment where each gripper is inflated to the same pressure value, the four-fingered gripper would be comparatively much more successful, especially considering it is the gripper with the lowest disparity in angle of curvature between fingers.

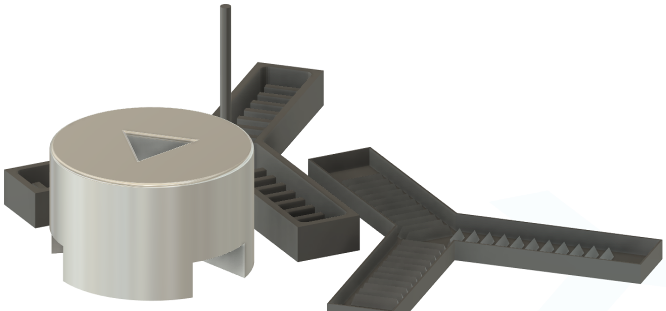
IV. Discussion

This experiment demonstrated that having more than two fingers makes the gripper performance more robust to changes in grasping orientation. The asymmetry of the three-fingered gripper was advantageous in some cases, like the cone, where two of the fingers could grip under the flat face and the third could secure the grip. It is logical to take inspiration from grasping mechanisms in nature as successful morphology is prioritised by natural selection. A key practical limitation across all the grippers was their delicate structure which was prone to bursting if pressure increased too rapidly or by too much. Separated pneumatic chambers such as those used by *Le et al.* [8] may offer more resilience against bursting as they are able to expand individually without the top surface connecting them being overly strained. The large expansion of the top surface is displayed by the inflated grippers shown in Fig. 4, particularly for those whose curvature angles are $\geq 70°$.

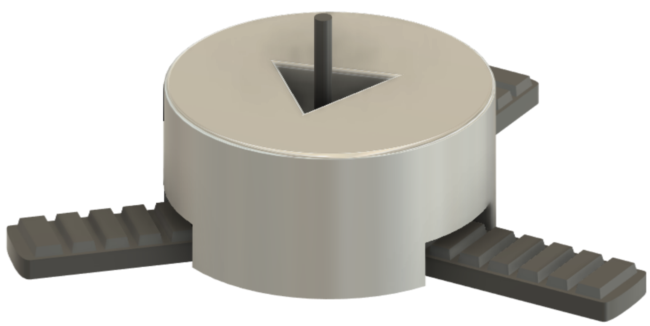
the limited volume of air due to pressurising with a fixed-volume syringe clearly played a role in the performance of the four-finger gripper in particular, which has more volume of pneumatic chambers to fill and thus achieves the least pressure of the three with the available volume of $60cm^3$ of air. This means on the smaller shapes, it was unable to acquire as tight a grasp as the other grippers and thus could not lift them, even if this gripper is more robust to changes in orientation than the other two. This is evidenced by its superior performance on the cuboid, a larger shape which thus required less air to deform tightly around. This would not be an issue in a commercial setting with pressurising systems that are not limited by volume. It is, therefore, logical to conclude that the three-fingered gripper structure had an advantageous balance between superior lateral enclosing to the two-fingered gripper while not increasing the volume of pneumatic chambers to the point at which high curvature angles were unachievable with the $60cm^3$ of pressurising air available.

Control over rotation is important to increase the gripper's versatility. Some orientations are Superior to others to increase contact between the gripper and the object. An actuated iteration of *Salem et al.*'s [7] soft wrist design which can rotate and bend, would allow the gripper to attempt grasping only in the most advantageous orientation, providing the greatest chance of a successful grasp and lift. This would be especially useful for asymmetrical grippers like the three-fingered gripper, which took a long time to stop spinning naturally on the point of the cone before grasping could be attempted.

Inspired by the studies by *Le et al.* & *Salem et al.* and learning from the three grippers fabricated for this study, an improved gripper design is presented in Fig. 6. Given its success experimentally, the bio-inspired asymmetrical three-fingered design was maintained. A lid mould was created to separate the pneumatic chambers to improve the structural robustness of the gripper at higher pressures and reduce instances of bursting. The wrist component slots over the arms of the gripper to prevent rotation as it lowers and contacts the object, allowing for intentional orienting of the gripper for maximum likelihood of a successful grasp and lift.



(a) Fixed Wrist Design (silver), Base Mould (Grey, Left), Lid Mould (Grey, Right).



(b) Fabricated and Assembled Gripper and Wrist.

Fig. 6. (a) displays the fixed wrist design along with the base and new lid mould for the asymmetrical three-fingered gripper. (b) displays the fabricated gripper assembled with the wrist.

Based on the insights discussed above, there are two important further studies which should be performed to conclusively compare the three grippers. First, the experiment should be repeated with each gripper inflated to a set pressure value, as opposed to with a fixed volume of air. This more closely mimics commercial settings where air supplies to pneumatic devices are not limited in volume and would not disadvantage larger grippers as this experiment has. Second, an actuated wrist should be developed to control gripper orientation when in contact with the object, such as the improved gripper and wrist given in Fig. 6. Again, this more closely mimics real-world applications where grippers will not be left to rotate freely as they grasp an object; in commercial settings, this could damage goods. Across various types of soft grippers, in the case that orientation is not actuated, it is always fixed [11]. Control of the orientation would compare each gripper's ability at the best possible orientation for a given object, likely leading to an increase in performance and versatility for all three grippers. In any further study, the improved gripper would be fabricated and compared to the three presented here. Through repeated iteration, soft grippers such as these will become versatile, accurate and structurally robust enough for widespread commercial use.

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