Analysis and Evaluation of a Manually Fabricated Pneu-Net Soft Gripper: A Comparative Study

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***Abstract*—This study assesses a manually fabricated soft gripper's performance in meeting grasping requirements for diverse objects within acceptable curvature parameters. While satisfactory, practical applications demand precise and rapid functionality across various objects. Drawing from prior research, including multi-layer fabrication and automated actuators, can advance gripper development. Exploring alternative materials like fiber-reinforced elastomer matrices or fluidic network actuation offers flexibility and lightweight benefits. Additionally, considering alternatives such as McKibben air muscles, tactile sensors, and camera modules will enhance gripper performance for real-time tracking and intelligent detection, facilitating their adoption in robotics applications.**

***Index Terms*—soft gripper, pneumatic,texture analysis**

I. Introduction

The cornerstone of any product-centric industrial enterprise lies in its initial phase: manufacturing. The company's profitability and market demand hinge significantly on the efficiency and speed at which duplicates of a prototype can be reproduced, while minimising energy expenditure and maximising efficiency. Within the manufacturing sector, terms like "Robot," "Autonomy," and "Intelligent" are frequently talked about. The advent of the 21st century has witnessed a notable surge in autonomous manufacturing processes, with an increasing number of companies embracing these systems to enhance their bottom line. Conventional manufacturing systems typically comprise rigid components interconnected by joints with limited ranges of motion [1], rendering them ill-suited and inflexible for safe operation within dynamic environments. Moreover, they often demand precise machining, labor-intensive assembly procedures, and integration of multiple onboard sensors [2]. These challenges have spurred innovation in manufacturing methodologies, giving rise to a new frontier in robotic autonomy: soft robotics.

Soft robots leverage highly deformable and compliant materials capable of sustaining significant, repeatable deformations [3]. Inspired by biological structures like muscular hydrostats found in squid tentacles, elephant trunks, and lizards' and mammals' tongues [4] [5], these robots mimic natural dexterity. The human hand, renowned for its remarkable dexterity, serves as inspiration for man-made modifications such as soft elastomer grippers, gaining traction in industrial applications due to resilience and compliance [6]. These grippers bridge the human-machine gap by emulating grasping actions without causing damage, suitable for manufacturing and packaging operations by conforming to object shapes. Smart and soft materials like shape memory alloys, polymers, and hydrogels have been employed in developing grippers for soft robotic applications [7].

This study investigates fluidic elastomeric soft grippers, employing pneu-net (pneumatic) actuators for various deformation modes and gripping capabilities [3]. Such actuators are favored in soft robotics for their rapid manufacturing techniques. Research on grippers assesses their grasp ability and performance in diverse scenarios. For instance, Katzschmann et al. [8] compared a soft gripper with a traditional rigid one in pick-and-place experiments with over seventy objects. Soft grippers were also used for biological sampling on deep reefs [9]. Investigations into starfish-like [10] and anthropopactic [11] soft grippers demonstrated successful grasping and manipulation of various objects. However, gripper fabrication can involve complex manual processes [12]. Ilievski et al. [13] demonstrated promising outcomes with a multi-layer fabrication strategy, leveraging PDMS and Ecoflex 00-30 for their distinct properties. Zhongkui et al. [12] utilised motors and sensors for gripper actuation, while Charbel et al. [3] and [14] developed grippers with suction pads, soft tips, and automated actuators. Additionally, [15] presented a gripper employing triple-layer fabrication with a fiber-reinforced elastomer matrix.

This investigative study aims to delve into the capabilities of the manually fabricated pneu-net soft gripper, particularly focusing on its gripping performance across various objects of diverse compositions and weights. Additionally, the study will investigate the impact of integrating additional grip-enhancing materials on the gripper's functionality. By thoroughly examining these factors, we seek to gain valuable insights into the potential applications and future developments of this technology.

II. Design & Methodology

A. Design Fabrication

Working principcle of Pneumatic Systems: Air, with its low viscosity and compressibility, allows for rapid actuation and easy storage, making it lightweight and environmentally

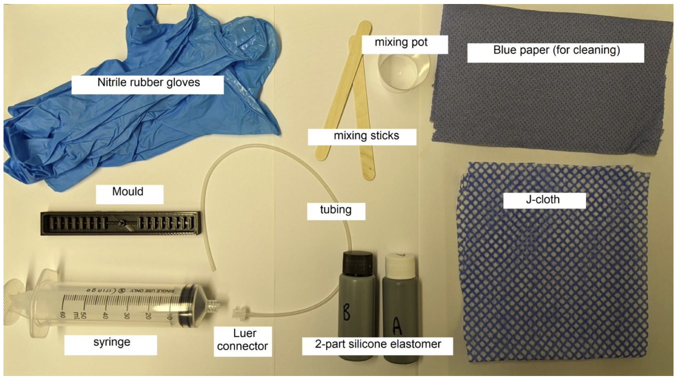

Fig. 1. DIY Kit [16]

friendly. Pressurisation causes expansion in the most compliant or least stiff regions of channels, typically defined by thin walls. This expansion further thins the walls and increases the channel volume, leading to bending of the surrounding structure to accommodate the elongation. In homogeneous elastomers, pressurization of a single channel causes bending of the surrounding slab, while multiple channels can generate complex shapes in elastomeric structures [13].

Experiment: A take-home kit consisting of Ecoflex 00-30, a two-part silicon elastomer, along with a curing mould and necessary accessories, was utilised for crafting the pneu-net soft gripper as shown in Fig. 1. The fabrication process typically spans 8-9 hours. Given the considerable time investment, precision is paramount to avoid inadvertent flaws that may necessitate redoing the procedure, impacting overall efficiency. The fabrication process can be outlined as follows:

- Combine equal parts of the two-part Ecoflex in a tray and mix thoroughly for one minute.
- Transfer the mixture into a 60mL syringe, and eliminate any air bubbles by covering the syringe tip with your thumb to create a vacuum and repeating till no bubbles persist.
- Affix the silicone tubing to the center of the mould, then pour the silicone mixture evenly into the mould.
- Pour the remaining mixture onto the jaycloth to create a sufficiently thick base layer. Allow the setup to cure for 4 hours.
- Remove the solidified silicone from the mould, and utilise a fresh mixture of equal parts of the two-part Ecoflex to uniformly adhere the silicone to the base silicon. Strengthen the tube attachment point and edges with the remaining Ecoflex mixture.
- Let it rest for 4 hours. Attach a smaller syringe tip to the syringe base, connect it to one end of the silicone tubing, and pump air. Your soft gripper should fold like a claw, capable of grasping objects.

B. Experimental Setup

Three grippers with differing amounts of deformation capacities have been fabricated.

Model Name	full compression volume (mL)
Gripper 1	60
Gripper 2	45
Gripper 3	50

TABLE I
MODEL INFORMATION

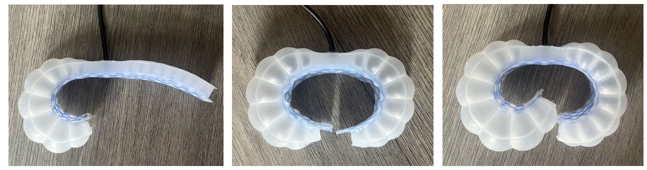

Fig. 2. (**a**) - gripper 1, (**b**) - gripper 2, (**c**) - gripper 3

Fig. 2. and Table I shows the three fabricated grippers in question as well as the maximum air pumped into it for full deformation/inflation. Description of grippers are as follows:

- **Gripper 1:** Non-uniform deformation and inflation across both ends.
- **Gripper 2:** Uniform deformation and inflation across both ends.
- **Gripper 3:** Uniform deformation and non-uniform inflation across both ends.

The grippers and the syringe for pneumatic actuation will be manually handled whilst the grasping action of the gripper is captured on a phone balanced on a stand. Image analysis of grasping will provide us with the curvature values for further analysis.

These grippers of different grip strengths and deformation will be tested against various random objects of daily use which are commonly manufactured in bulk quantities handled by a automated machine with grippers. The **metric** of evaluation will be based on the deformation of the gripper's curvature, the coefficient of friction of the surface of the object, weight of the object, and effect of external attachments on the silicon grip efficacy. This will help evaluate the effectiveness of the gripper against a range of weight and coefficient of friction values improving upon which further research can be conducted.

C. Python Code:

One of the metrics of evaluation to measure deformation and the bending of the soft elastomer gripper to conform to the shape of the object used is the Curvature equation from Geometry in Mathematics. It is a measure of the deviation of a set of adjoining points from the straight line. The equation employed for calculating the curvature is the mathematical representation of curvature for a parametric curve, specifically in the context of quadratic curve fitting:

$$C = \frac{2 * A}{(1 + (2Ay + B)^2)^{3/2}} \tag{1}$$

where A,B are coefficients in Eq. 1.

For the pre-requisite to the python code the images of the grippers were marked with 'red dots' as point of interest for curve fitting task to be computed by the code as shown in Fig. 3.

Fig. 3. (**a**) - gripper 1, (**b**) - gripper 2, (**c**) - gripper 3

The Python code analyses and visualises red-coloured objects in an image. It imports NumPy, OpenCV (cv2), and scipy.interpolate libraries. The main function loads an image and isolates red regions using HSV colour space conversion and thresholding. Contours within these regions are identified, and their centers are sorted vertically. Duplicate x-values are removed, and cubic spline interpolation creates a smooth curve connecting sorted centers. Curvature is then calculated along the curve using numerical derivatives. Finally, the interpolated curve is overlaid onto the original image for visual inspection.

Note: Each image from Fig. 2. has been split into left hand-side (LHS) and right handside (RHS) due to computational flaws in the imported interpolation function. Consequently the computed curvature is taken as the mean of the LHS and RHS.

III. Results & Analysis

A. Curvature:

Each of the fabricated grippers due to unintended manual fabrication constraints have been cured different from the other as evident from Fig. 1 due to which it poses a significant difference in their performance of their gripping ability of objects. Gripper specific analysis of the practicability are discussed below.

Model Name	RHS Curvature	LHS Curvature	Mean Curvature
Gripper 1	0.000956464	0.004545001	0.002750732
Gripper 2	0.003010713	0.004113017	0.003561865
Gripper 3	0.003721504	0.002943726	0.003332615

TABLE II
Computed Curvature

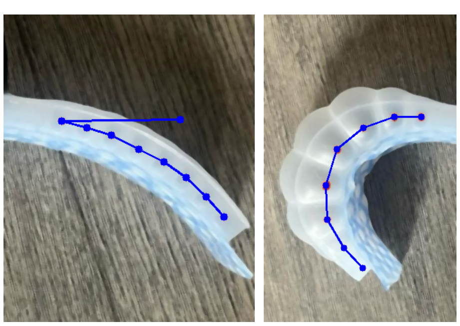

Fig. 4. (**a**) - gripper 1 RHS, (**b**) - gripper 1 LHS

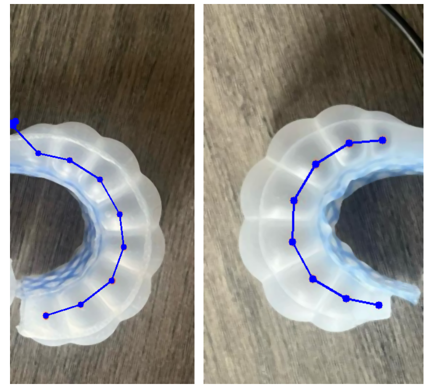

Fig. 5. (**a**) - gripper 2 RHS, (**b**) - gripper 2 LHS

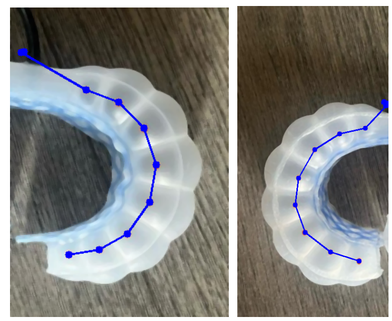

Fig. 6. (**a**) - gripper 3 RHS, (**b**) - gripper 3 LHS

Table II presents the curvature measurements computed from the Python code's analysis of the images depicted in Fig. 3 who's results are shown in Fig. 4,5,6. A comparison between Table II and Fig. 2 reveals that Gripper 1 exhibits non-uniform deformation along its length, resulting in curvature values approximately 20% lower than those of Gripper 2 and Gripper 3. Gripper 2 and Gripper 3, characterised by a more symmetrical deformation pattern across both ends, display higher curvature values in comparison. These values translated into a research **hypothesis** to deduce from further experimentation: *Gripper 1 will perform significantly subpar compared to either of Gripper 2 or 3 due to its fabrication abnormality.*

This abnormality stems from uneven air flow between the left and right hand chambers. The bias towards the left side causes full deformation before the right side receives air. An improvement suggestion is using a syringe with over 60mL capacity, but this risks overloading the left side, potentially causing a pop or air leak, rendering it inoperable.

B. Object Handling:

On testing the three grippers with traditional pick-and-place operation with objects of day-to-day use, the **hypothesis** stated under **II.B.Experimental Setup** can be proven. Due to the non-symmetrical deformation and curvature of Gripper 1, its performance has proven to be **significantly worse** than Gripper 2 and 3. The table below highlights the performance of the activity based on a simple Yes(Y)/No(N) scale with corresponding coefficient of friction values of the materials of the object [17].

Item Name	Coefficient of Friction	Weight (g)	Gripper 1	Gripper 2	Gripper 3
Medicine packaging (hard paper)	0.4	15	N	Y	Y
Mouse	0.11	73	N	Y	Y
Comb	0.45	81	N	N	N
Egg	0.2	61	Y	Y	Y
Airpods Case	0.4	81	Y	Y	Y
Wallet	0.6	124	N	N	N
Pen	0.45	18	N	Y	Y
Plastic medicine bottle	0.3	77	N	Y	N

TABLE III
OBJECT HANDLING DATA

Table III presents the results of the object picking experiment with the three grippers in question. From further analysis during experimentation several key points have been discovered:

- Maximum weight limit for object grasping should be less than **100g**.
- Objects with non-uniform weight distribution such as the comb found it harder to be grasped as compared to other objects with uniform weight distribution.
- Objects with small diameter and length greater than 15cm had issues with stability after grasping i.e; comb and pen.
- If the object's linear dimensions (length, breadth or height) fall within 60% of the gripper dimensions ($\simeq 12cm$), a 30mL air volume of the syringe pump is enough for actuation and a good grip.
- Correspondingly, for spherical and cylindrical objects, if the length of the gripper is more than half the circumference of the object, a 40mL air volume of the syringe pump is enough for actuation and a good grip.
- Gripper 3 exhibits non-uniform inflation, depicted in Fig. 2(c), resulting in slippage during object gripping(Table III. Plastic medicine bottle). This asymmetrical deformation causes one side to deform slightly earlier and to a greater extent than the other side, in contrast to the performance of Gripper 2.
- Gripper 2 requires 1.85 seconds to fully deform around a cylindrical bottle for grasping whereas Gripper 3 requires 3.09 seconds due to its non-uniform deformation.
- The inherent adequacy of Elastomer 00-30's coefficient of friction meant that the object's coefficient of friction had minimal impact on the gripper's grasping capability. Nevertheless, in scenarios involving heavier objects with diverse finishes, a gripping surface possessing a higher coefficient of friction could offer practical advantages in countering external disturbances.
- Practically speaking, manual simulation of a moving belt revealed that an optimal grasping of the object occurs at an average speed below 3 cm/s.

In summary, the two-fingered soft gripper performed adequately, gently gripping various bulk-handled objects without damage. While the silicone grip was sufficient, adding textural features could enhance its versatility. However, it struggled with plastic materials due to low friction, suggesting a need for suction cup mechanisms.

Note: The above deductions are solely based on the objects chosen for experimentation. Error margins are to be considered for objects outside this dataset for reasonable accuracy of operation.

The curvature values for the non-loaded state depicted in Table II were cross-verified with a loaded-state using a hard paper packaging for soap and an airpods case. The curvature values computed were lower than the fully actuated state (Fig. 2 and Table II) - $\simeq 0.0027$ for the airpods case (Fig.7(a), 8(a)) , and $\simeq 0.0025$ for the soap package (Fig. 7(b), 8(b)), as expected due to the space now occupied by the object. In compliance with bullet point 4 as stated above: "If the object's linear dimensions (length, breadth or height) fall within 60% of the gripper dimensions ($\simeq 12cm$), a 30mL air volume is enough for actuation and a good grip", it has been noted that the actuation air volume of 30mL such that the gripper ends are almost parallel to the object surface is sufficient for good grip as shown in Fig. 7(b).

Fig. 7. (**a**) - gripper 2 with airpods, (**b**) - gripper 2 with soap package

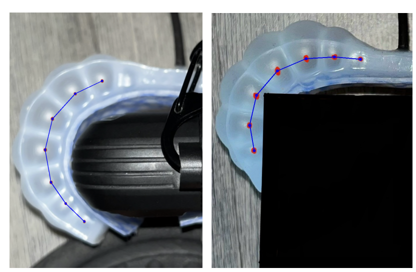

Fig. 8. (**a**) - gripper 2 with airpods, (**b**) - gripper 2 with soap package

Note: Fig. 7(b) has black mask on the packaging for computational needs to better the plotting of the curvature line. The gripper used here is gripper 2 as it is the best performing gripper having uniform inflation across both ends.

C. Modification:

Gripper 2, the most effective among the group, was enhanced for better grip strength. Silicon served as the contact surface for object manipulation. Modifications included attaching garlic granules and salt grains with glue to both contact ends, aiming to improve grip and compare outcomes with previous versions for future improvements.

Fig. 9. (**a**) - gripper 2 with garlic granules, (**b**) - gripper 2 with salt grains

The assessment of this external factor (modification) was conducted through experimentation using the same dataset of materials as utilised for Section III.B. Object Handling. Incorporating grains or granules demonstrated improvement under specific circumstances. For materials such as eggs, mouse, or polypropylene plastics commonly used in packaging, which possess smooth surface finishes, the introduction of granules or grains led to heightened slippage compared to the unmodified gripper. Conversely, when dealing with rough contact surfaces i.e; cloth, an interlocking mechanism was observed. However, if the granules or grains lacked a surface to interlock onto i.e; plastic, their effectiveness was compromised. Materials like cotton found in socks, featuring micro-pockets due to weave-like pattern due to their make, facilitated interlocking of salt grains and garlic granules, thereby enhancing grip.

Various other materials can offer good grip against surfaces, similar to grains and granules. Fine-grained sand, rubber crumbs, and sawdust provide excellent traction, particularly on surfaces like wood or concrete. Rice grains and ground coffee create additional friction on smooth surfaces like glass or ceramics. Polymer beads and crushed walnut shells offer cushioned grip and rough texture, suitable for non-slip coatings or abrasive applications. Silica gel beads provide a textured surface with good grip, especially on smooth surfaces like glass or metal. These materials can be utilised in diverse applications to enhance traction and grip [18].

IV. Discussion & Future Work

Extensive investigation has been conducted into the capabilities of the manually fabricated soft gripper across a diverse array of mass-produced everyday items. Encouragingly, it has exhibited satisfactory grip strength for the utilised dataset and meets the baseline requirements of a soft gripper. Nevertheless, transitioning this solution to practical applications necessitates comprehensive restructuring, encompassing fabrication methods, actuation mechanisms, and potentially design modifications to optimise grip performance, particularly concerning the materials encountered in daily use.

Setting up the research experiment posed inherent fabrication challenges, particularly concerning the curing process, which required approximately 8 hours per gripper if executed flawlessly. However, numerous attempts were often thwarted by issues such as air leakage or popped air bubbles during actuation, rendering many trials void. Consequently, the fabrication process had to be repeated approximately 8 times to achieve an optimal result, resulting in significant time and resource wastage. Moreover, the limited utility of a two-finger gripper compared to a three-finger claw gripper is notable, with the former often requiring soft pads or suction enhancements to improve grip in other research studies [3] [14]. The results obtained demonstrate that the fabricated gripper meets the baseline requirements by effectively gripping random objects within an acceptable range of curvature. However, practical application demands precise and rapid functionality across a wide range of objects. Drawing inspiration from research studies such as [13], which utilise multi-layer fabrication, or [3] [14], which implement automated actuators for three-finger grippers, or [12] [14], which integrate sensors for measuring variables like force and curvature, can aid in advancing the current state of manually fabricated grippers. Exploring alternative build types, such as utilising a fiber-reinforced elastomer matrix [15], or incorporating an actuating mechanism using fluidic networks, may offer potential benefits such as increased flexibility and lightweight design. Optimising the resting angle to be less than 90 degrees to the perpendicular can effectively limit the range of motion, ultimately resulting in time savings. Additionally, considering alternatives like McKibben air muscles, which mimic human muscles and offer lightweight, flexible, and versatile motion capabilities, could be advantageous. Moreover, integrating tactile sensors on gripper tips to measure force, capture pressure distribution, analyze texture, and monitor temperature can provide valuable parameters for evaluating gripper performance. Furthermore, incorporating a camera module to track real-time coordinates of objects for improved accuracy and precision, along with implementing a vision algorithm to intelligently orient and detect objects, can enhance gripper efficiency.

V. Conclusion

In conclusion, this study has provided a thorough analysis of the performance of three manually crafted soft grippers employing Ecoflex 00-30. Through the evaluation of metrics such as weight, coefficient of friction, and object dimensions, we have gained valuable insights into the capabilities of these grippers. We have also critically reviewed fabrication challenges, comparing them with state-of-the-art grippers featuring advanced constructions and external modules. Additionally, suggestions for enhancing the design through the incorporation of various attachments have been proposed for future research endeavors. Overall, this foundational gripper model represents a promising advancement in the manufacturing and healthcare sectors, particularly noteworthy for its flexibility and adaptability in contemporary contexts.

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