Journal of Al-Azhar University Engineering Sector

Vol.18, No. 69, October 2023, 973 - 985

INFLUENCE OF ACTUATOR MORPHOLOGY ON GRASPING PERFORMANCE OF SOFT ROBOTIC GRIPPERS IN AGRICULTURE: SIMULATION STUDY

Mahmoud Elsamanty[1,2], Nourhan Hafez[1], Saber Abd Rabbo[1], Mohamed Ib. Sokar [1,*]

[1] Mechanical Engineering Department, Faculty of Engineering at Shubra, Benha University, Egypt.
[2] Mechatronics and Robotics Department, School of Innovative Design, E-JUST, Egypt.

* Correspondence: mohamed.sokar@feng.bu.edu.eg

Citation:

M. Elsamanty, N. Hafez, S. Abd Rabbo, M. I. Sokar " Influence Of Actuator Morphology on Grasping Performance of Soft Robotic Grippers in Agriculture: Simulation Study", Journal of Al-Azhar University Engineering Sector, vol. 18, pp. 973 – 985, 2023

Received: 22 June 2023

Accepted: 24 August 2023

DoI:10.21608/auej.2023.219521.1385

ABSTRACT

Soft pneumatic actuators (SPAs) with tailored actuator morphology are extensively employed in precise agriculture for cultivating sensitive crops. This study investigates the impact of varying the geometrical parameters of the elastomer finger, specifically the rib pitch (P_r) and finger width (w_f), on the SPA bending variables, including deflection angle (Ø) and deflection along the X- and Y-axis. Sample SPAs were fabricated to validate Yeoh's 3rd-order model. All designed molds used to cure the soft elastic finger (elastomer) were created on a 3D printer.

Finite element analysis (FEA) was conducted by ANSYS to analyze the impact of each geometrical parameter individually and continuously varied along the longitudinal axis. The FEA results indicate a variation in the deflection angle from 13.01° to 108.50°. Furthermore, the deflection along the X-axis ranges from 0.85 mm to -213.54 mm, while the Y-axis varies from 32.55 mm to 148.45 mm. The study demonstrates that the geometrical parameters of the elastomer finger significantly influence SPA bending variables, with the rib pitch (P_r) exerting a greater impact on the deflection angle than the finger width (w_f). The deflection on the X-axis exceeds that on the Y-axis. The findings of this study can inform the design of SPAs with tailored actuator morphology and bending properties for precise agriculture applications.

KEYWORDS: Soft robotics, Precise agriculture, Hyper-elastic material, Sensitive crops, and soft gripper actuator (SPA).

تأثير شكل "مورفولوجيا" المشغل على أداء المسك لقوابض الروبوتات اللينة في الزراعة: دراسة محاكاة

محمود السمنتي[1،2]، نورهان حافظ[1]، صابر عبد ربه[1]، محمد سكر[1،*]

[1]قسم الهندسة الميكانيكية، كلية الهندسة بشبرا، جامعة بنها، القاهرة، مصر

[2]قسم الميكاترونيات والروبوتات، مدرسة التصميم الابتكاري، الجامعة اليابانية، الاسكندرية، مصر

***البريد الاليكتروني للباحث الرئيسي:** mohamed.sokar@feng.bu.edu.eg

الملخص

تُستخدم المشغلات الهوائية اللينة (SPAs) المزودة بتشكيل مشغل مخصص على نطاق واسع في الزراعة الدقيقة، لزراعة المحاصيل الحساسة. تبحث هذه الدراسة في تأثير تغيير المعاملات الهندسية لإصبع المطاط الصناعي، وتحديداً خطوة الضلع (P_r) وعرض الإصبع (w_f) ، على متغيرات الانحناء SPA ، بما في ذلك زاوية الانحراف (Ø) والانحراف على طول X- و Y- محور. تم تصنيع عينة SPAs للتحقق من نموذج Yeoh من الدرجة الثالثة. تم إنشاء جميع القوالب المصممة المستخدمة لصب الإصبع المرن الناعم (المطاط الصناعي) باستخدام طابعة ثلاثية الأبعاد. تم إجراء تحليل العناصر المحدودة

(FEA) لتحليل تأثير كل معامل هندسي على حدة ومتنوعة باستمرار على طول المحور الطولي. تشير نتائج FEA إلى اختلاف في زاوية الانحراف من 13.01 درجة إلى 108.50 درجة. علاوة على ذلك، يتراوح الانحراف على طول المحور X من 0.85 مم إلى -213.54 مم، بينما يتراوح المحور Y من 32.55 مم إلى 148.45 مم. توضح الدراسة أن المعاملات الهندسية للإصبع المطاطي تؤثر بشكل كبير على متغيرات الانحناء SPA، حيث يكون لخطوة الضلع (Pr) تأثير أكبر على زاوية الانحراف من عرض الإصبع (w_f). يتجاوز الانحراف على المحور "س X" ذلك على المحور "صY ". يمكن لنتائج هذه الدراسة أن تفيد في تصميم SPAs مع مورفولوجيا المشغل المصممة خصيصًا وخصائص الانحناء للتطبيقات الزراعية الدقيقة.

الكلمات المفتاحية : الروبوتات اللينة ، الزراعة الدقيقة، المواد فائقة المرونة، المحاصيل الحساسة، ومشغل القابض الناعم (SPA).

1. INTRODUCTION

Soft robotics is an emerging field in robotics research that has the potential to revolutionize the role of robots in society and industry. Despite its promising future, the field is relatively small. According to a literature study, the term "soft robot" was initially used to describe a rigid pneumatic structure with some degree of object compliance due to gas compressibility. In 2008, "soft robotics" was introduced to describe research on robots with compliant joints and Actuator Morphology based on soft materials with flexibility, deformability, and large-scale adaptability [1, 2] . However, pursuing radically different robots from their traditional rigid counterparts began long before technical terminology emerged. For instance, in the 1950s, McKibben invented braided pneumatic actuators for polio patients to use as an orthotic brace. The artificial McKibben muscle has since been widely studied and used in various robot design forms [3]. In 1990, Matsumoto and Shimachi recorded their work on soft fingers, and one year later, Suzumori et al. released their elastic micro actuator made of silicone rubber and explored many applications [4–5] .

The final effector is a crucial component of a robot system that defines its function. However, grippers can only capture one or a few objects simultaneously [6]. Although dexterous grippers provide better grasping capabilities, they are often too expensive, complex to control, and unsuitable for industrial use. To overcome these limitations, researchers have explored soft robotics principles and the development of low-cost grippers that can handle various objects without requiring complex control procedures [7]. Due to its low cost, ease of use, and lack of need for sophisticated technology or highly experienced labor, silicone elastomers are receiving a lot of interest as a material suitable for soft grippers. These compatible materials are especially advantageous when considering the safety of interacting with biological products, which qualifies them as suitable options for agricultural applications [8]. A fruit harvesting method that includes a novel compact, compliant soft robotic gripper, and a twist-pulling motion was proposed and implemented by [9] to detach the apples from the trees with large grasping force to achieve apple harvesting in the natural orchard.

Two soft-end effectors have been designed and constructed, with their physical structure, characteristics, and operational performance analyzed. These soft grippers are deformable and adaptable, enabling easy and efficient control with minimal planning, and their soft nature makes them well-suited for handling delicate and sensitive objects [10]. In robotic applications, the ability to grasp and manipulate objects safely is essential, and the design of end effectors must be distinct and complex enough to handle objects of different sizes, shapes, materials, and weights [11]. However, the complexity of the design can lead to a complicated control system. Researchers have investigated methods for demonstrating bending behavior in these actuators. Extender muscles have been shown to produce bending movement when formed into a continuum brace of parallel muscles A new bending muscle based on a single extender actuator that can generate a bending motion has been proposed in [8, 11].

A novel bending muscle design which is based on a contractor actuator that contracts to activate the muscle and cause bending was presented. A thin, incompressible, and flexible reinforcing rod with a thickness of 2 mm is inserted between the inner tube and the muscle's braided sleeve to prevent unilateral contraction [12–14]. The first gripper used was capture-friendly and can support a weight of up to 1.4 kg across a broad range of grab sizes for various object shapes and sizes. The softness of the fingers was adjusted by regulating the air pressure within the fingers without the need for a complex control system or grasp planning to conform to the shape of an object. The extension circular gripper has two main features that can be extended to allow for the appropriate positioning of the object in the grip's main contact area [15]. The second feature is a circular shape that reduces in diameter when subjected to pressure, allowing the object at its center to be grasped. Experiments have shown that the gripper can lift a maximum weight of 10.9 kilograms. Two grippers have been modified to improve their performance, and each one is equipped with a control system to assess design efficiencies in [16, 17].

These grippers are highly suitable for a variety of tasks such as warehouse logistics involving objects of varying sizes, advanced assembly tasks that currently require significant labor, and food handling, where sanitation and delicate manipulation are essential. The end effectors enable packaging, food, beverage, and industrial robots to handle a variety of objects using a single, user-friendly device, eliminating the need for tool changes and complex vision requirements. The Soft Robotics control unit is a high-speed (>3 Hz) controller with a millisecond response time, guaranteeing consistent and repeatable actions. It is compatible with every commercial robot controller [18], [19]. It offers turnkey integration, allowing users to quickly install and commission the system for new or retrofit applications with no additional components or control hardware. In addition, the study shows that larger objects are relatively easier to grasp and raise compared to smaller and softer objects. The main contributions of this study include the development and assembly of an easy-to-manufactured soft gripper, the analysis of soft finger and soft gripper targets to analyze soft robotic dynamics, and different finger designs [4]. In this study, the authors provided a detailed description of the geometry of the bellows and highlighted its significance in predicting the functionality of soft robots before fabrication.

By utilizing the geometric characteristics of the bellows and specific metrics tailored to the application, designers can anticipate important features such as the robot's curving angle and blocking force. This approach, coupled with advanced actuator models and 3D multi-material printing, has considerably broadened the potential applications of practical soft robotic systems. Furthermore, the design framework presented here enables the rapid development and manufacturing of soft robots that meet functional requirements, thereby unlocking new possibilities for soft machinery [11, 17]. A multivariate optimizer strategy could be employed to adjust the geometry of the bellows, materials, and actuation pressure, ensuring that the robot meets its intended limitations. In certain applications, it may be necessary to impose additional constraints on the drives, such as considering both the bending and force design of the actuator while ensuring the lowest possible stress to achieve a longer service life.

Based on the existing literature, there is a knowledge gap regarding the impact of altering the actuator morphology design parameters on the model's behavior. This study aims to investigate the influence of these parameters on the grasping force and positioning of the gripper using Finite Element Analysis (FEA) in ANSYS. The results of FEA indicate that these pneumatic actuators can achieve significant deflections at relatively low pressures.

The paper is structured as follows: Section 2 presents the model design and material characteristics, followed by the demonstration of the finite element analysis in Section 3. The resulting curves are then discussed in Section 4.

2. Design Variables in CAD Model

The subject of this study is the morphology of a soft pneumatic actuator (SPA) designed using computer-aided design (CAD) software SOLIDWORKS, as depicted in **Fig. 1**. The study aims to investigate the effect of varying actuator morphology parameters on the bending envelope of the SPA at different pressure levels ranging from 10 to 50 kPa. Specifically, the study varies the rib pitch (P_r) and the finger width (w_f), while keeping the number of ribs constant at five and other parameters, such as rib width (w_r), finger height (h_f), rib height (h_r), and upper thickness (t_u), fixed. By investigating the influence of these actuator morphology parameters on the bending behavior of the SPA, this study seeks to improve our understanding of the factors that affect the bending performance of soft pneumatic actuators, which could lead to the development of more efficient and effective soft robotic systems. **Table 1** summarizes the pressure levels used in this study, and the results are presented in subsequent sections of the paper.

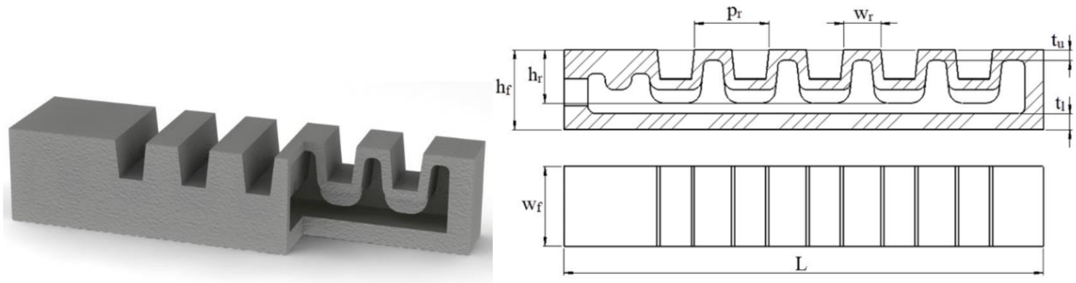


Fig. 1. Morphology of the soft pneumatic actuator (SPA) designed using computer-aided design (CAD) software SOLIDWORKS.

Table 1. The effect of varying t_u and w_r on the work envelope

L (mm)	t_u (mm)	w_r (mm)	w_f (mm)	h_f (mm)	h_r (mm)	t_l (mm)	P_r (mm)	Pressure p (kPa)
140, 165, 190	2	10	30, 35, 40	30	15	8	20, 25, 30	10-50

2.1. Material characteriscts

It is an important process to understanding a material's physical and mechanical properties and its impact on the actuator morphology's behavior in real-world applications. The silicone material used in fabricating the soft gripper is DC-A10, a hyper-elastic material with high flexibility and elasticity. DC-A10 is a two-part silicone rubber that belongs to the platinum-cured type, with a mixing ratio of 10:1. This type of silicone rubber is widely used in the soft robotics industry due to its superior mechanical properties, such as high elongation at break, high tear strength, and excellent resistance to aging and weathering. To better understand the physical and mechanical properties of DC-A10 and its impact on the actuator morphology's behavior, a material characterization process was conducted, which involved several tests and measurements, such as tensile testing, compression testing, and hardness testing. The results of these tests were used to determine the material's elastic modulus, Poisson's ratio, and other key parameters that affect its behavior under different loading conditions. **Table 2** presents the technical parameters of the DC-

A10 silicone material, including its density, viscosity, and curing time. Understanding the material properties of DC-A10 is crucial in designing and optimizing the actuator morphology, as it allows for selecting the most suitable material parameters and design features that can enhance its performance and durability. Additionally, the material characterization process provides valuable insights into the limitations and challenges of using hyper-elastic materials in soft robotics applications, enabling researchers and designers to overcome these challenges and develop more advanced and efficient soft robotic systems.

Table 2. Hyper-elastic material DC-A10 properties. [20]

Model	DC-A10
Color	Translucent Adjustable
Mixing ratio (%)	1:1
Pot life (mins, under 25°C)	20-40
Curing time	(3-5hrs under 25°C); (20-30 mins under 60°C)
Hardness (Shore A)	10±2
Tensile strength (MPa)	>4.5
Tear-strength (kN/m)	>15
Viscosity (After A/B mixed, mPa.s)	3500±1500
Shrinkage rate (%)	<0.1%
Elongation (%)	> 500%

3. Finite element

3.1. Hyperelastic model identification

The soft gripper is operated solely in the longitudinal direction, emphasizing the necessity of developing an accurate constitutive model to characterize its behavior. To address this requirement, a specific constitutive model was formulated to depict the response of the gripper under uniaxial tension. The determination of Young's modulus, serving as an indicator of stiffness when subjected to external forces, was accomplished through a series of experimental tests, yielding a value of $E = 1.12$ MPa for the DC-A10 material. Poisson's ratio, which measures the relationship between transverse and axial strain, was also identified as $\nu = 0.15$, providing valuable insights into the material's deformation characteristics.

The validation of the constitutive model involved comparing the stress-strain curve obtained from experimental tests with the outcomes predicted by four distinct hyperelastic constitutive models. Notably, the stress-strain behavior of the 3D printed tensile specimen closely resembled the predictions of Yeoh's 3rd-order model, as visually depicted in **Fig. 2**. This observation highlights the remarkable capability of Yeoh's 3rd-order model to represent the gripper's response faithfully. Considering the exceptional agreement between the experimental stress-strain data and Yeoh's 3rd-order model, the latter was selected as the most suitable constitutive model for subsequent finite element analysis (FEA). By employing Yeoh's 3rd-order model in the FEA, the gripper's behavior can be reliably simulated under various loading conditions, enabling more accurate predictions and informed design decisions.

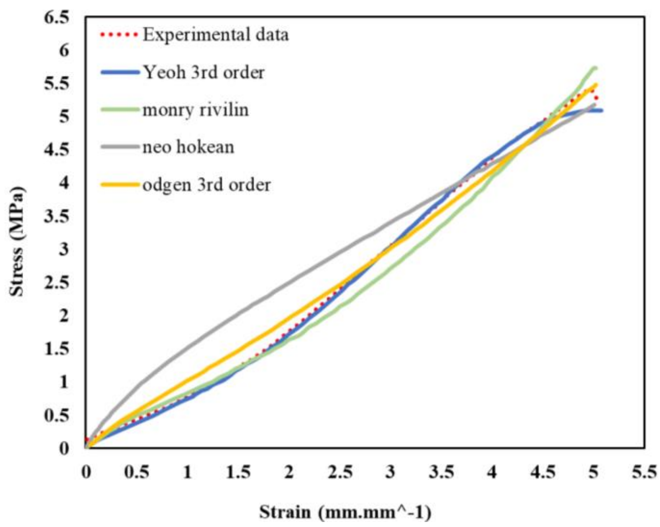


Fig. 2: The comparison of the experimental stress-strain data and the stress-strain predictions obtained from various available ANSYS hyperelastic models

3.2. FEA model

The finite element analysis (FEA) utilizes a hex-dominant meshing technique with a tri/quad element type. The mesh size employed in the FEA ranges from 3 to 5 mm, selected based on a comprehensive evaluation of solutions obtained using mesh sizes ranging from 1 to 5 mm. This selection balances computational efficiency and solution accuracy, as the solution has successfully converged at this mesh size. To prevent any interpenetration between the inner and outer surfaces during the application of atmospheric pressure output, frictional contact has been implemented.

The work envelope of the soft gripper represents the maximum point that the gripper tip can reach in the X and Y planes. To investigate this work envelope, a fixed support condition is imposed at the initial position of the gripper. The outer surface of the gripper is subjected to an atmospheric pressure of 1 bar to simulate ambient atmospheric conditions. Additionally, a pneumatic pressure denoted as p is applied to the inner surface, ranging from 10 kPa to 50 kPa in increments of 10 kPa. The simulation results encompass the final deflection angle (Ø) and the position of the soft gripper tip relative to the origin. The origin is defined as the midpoint of the fixed support surface, as illustrated in **Fig. 3**.

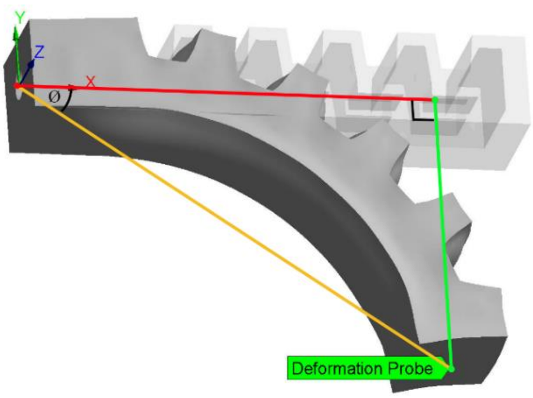
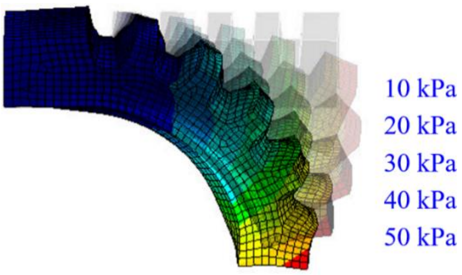
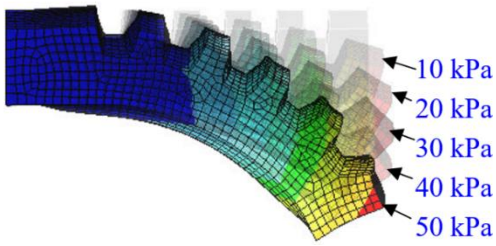


Fig. 3. Orientation of deflection angle (Ø) and tip coordinates in the soft gripper system

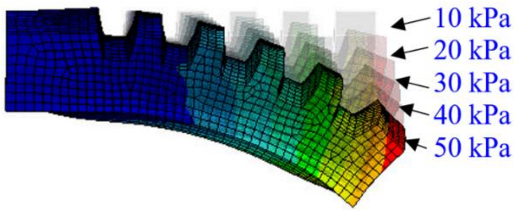
The Finite Element (FE) simulation is conducted using ANSYS software to explore the work envelope of the soft gripper finger. The investigation involves analyzing the impact of different values of finger width (w_f) and applied pressure (p) on the work envelope. The applied pressure ranges from 10 to 50 kPa with increments of 10 kPa, allowing for a comprehensive assessment of the gripper's behavior. The results reveal a clear correlation between w_f and Ø for a given pressure level. Increasing the finger width (w_f) increases the deflection angle (Ø) for the same applied pressure. This observation underscores the significance of varying finger width and applied pressure to achieve the desired deflection behavior. To visualize the cumulative effect of changing the finger width and the pressure, a series of accumulated images are presented in **Fig. 4**. These images provide a graphical representation of how the work envelope evolves as the finger width and applied pressure values change.



a) $w_f = 40$



b) $w_f = 35$



(c) $w_f = 30$

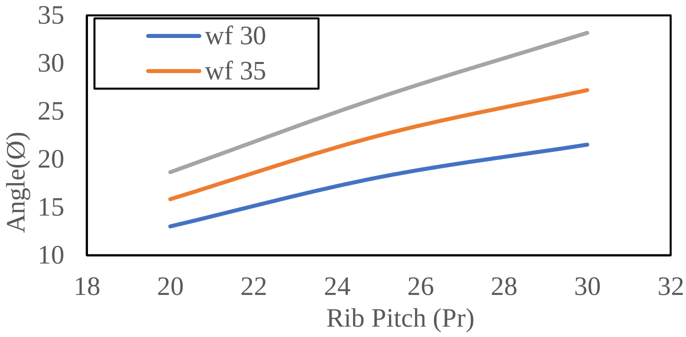
Fig. 4. The FEA simulation results of SPAs under different finger width (w_f) values and applied pressure (p)

4. Simulation Analysis of Soft Gripper Behavior

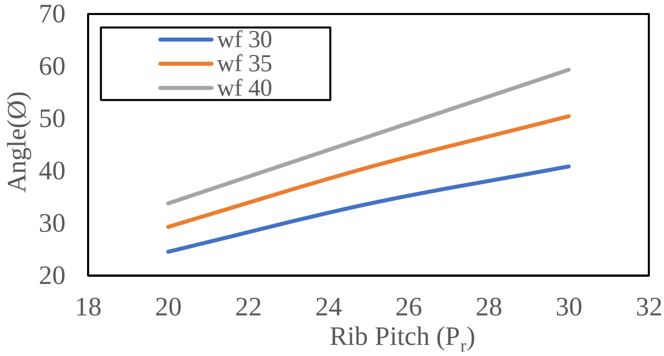
This section investigates the impact of pressure variation on the deflection angle (Ø) of the Soft Gripper, considering different values of t_u and w_r. The deflection along the X-axis is denoted as X, while the deflection along the Y-axis is examined using ANSYS software. ANSYS results are represented through 2D curves, enabling the simulation of the Soft Gripper's behavior under varying pneumatic pressures (p) and both of P_r, w_f values, while maintaining of w_r, h_f, h_r, and t_u at constant values. Data analysis is conducted for 45 points, as depicted in each figure, showcasing the deflection angle (Ø), displacement in X and Y changes with respect to different P_r, w_f, and p values. The simulations gradually vary P_r and w_f from 30 mm to 40 mm in 5 mm increments for each iteration. The pressure values examined are 10, 30, and 50 kPa for each P_r, w_f pair.

4.1. Deflection angle (Ø)

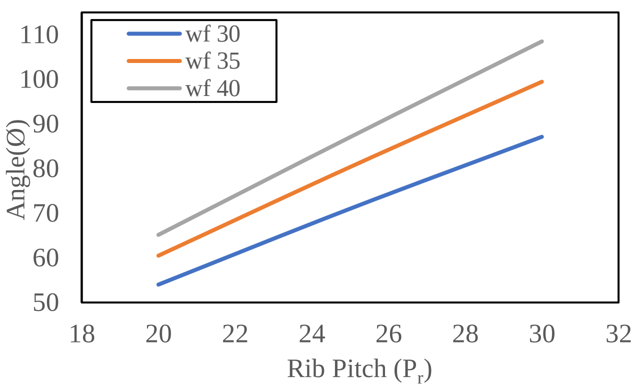
The analysis of the results reveals a noticeable trend: an increase in the value of p (pressure variation) leads to an increase in the deflection angle Ø of the Soft Gripper. This implies that higher pressure values applied to the Soft Gripper result in larger deflection angles. Additionally, the deflection angle Ø increases with both the finger width (w_f) and rib pitch (P_r). These observations are supported by the findings in **Fig. 5**, where the variation in deflection angle Ø ranges from 13.01° to 108.50° for the investigated parameter variations. Notably, despite these variations in P_r, w_f, and p, they do not significantly alter the overall trend exhibited by the deflection angle Ø as demonstrated in the curve analysis. Thus, the deflection angle Ø exhibits a consistent response to changes in these parameters, reflecting the influence of P_r, w_f, and p on the deflection behavior of the Soft Gripper.



a) P = 10 kPa



(b) p = 30 kPa

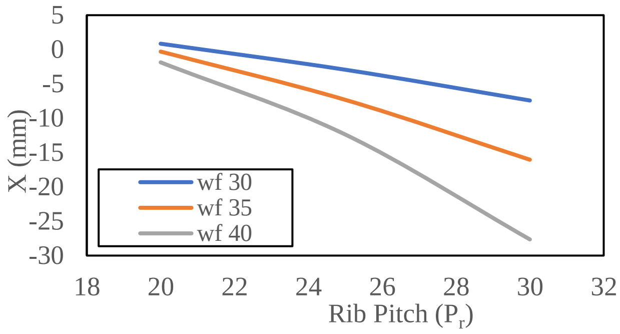


(c) P = 50 kPa

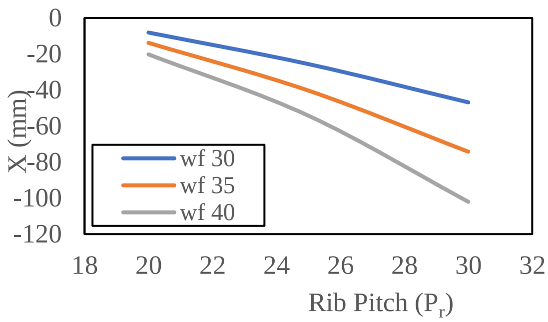
Fig. 5: Influence of Variation of Pneumatic Pressure, Rib Pitch, and Finger Width on Deflection Angle (Ø) of the Soft Gripper

4.2. Deflection on the X-axis (X)

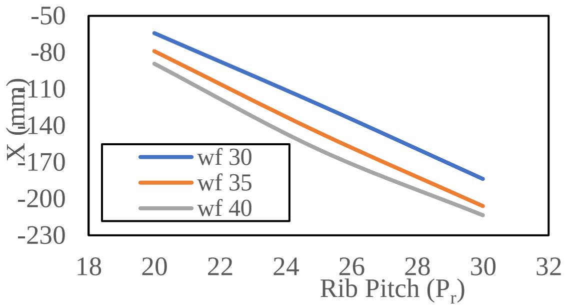
The analysis of the results further reveals another significant trend with respect to the deflection in the X-axis. As depicted in **Fig. 6**, an increase in the pneumatic pressure (p) also increases deflection in the X-axis but in the negative direction. Similarly, an increase P_r and w_f leads to an increase in the deflection on the X-axis, albeit in a negative direction. Consequently, the curve representing the deflection in the X-axis exhibits a downward trend towards the minimum value. The data analysis demonstrates a considerable variation in the X-axis deflection, ranging from 0.85 mm to -213.54 mm, reflecting the influence of P_r, w_f, and p on the deflection behavior of the Soft Gripper. It is noteworthy that despite these parameter variations, the overall trend exhibited by the X-axis deflection remains consistent, as evidenced by the curve analysis. These findings underscore the robust and predictable response of the Soft Gripper to changes in P_r, w_f, and p, influencing the deflection behavior along the X-axis.



a) p = 10 kPa



(b) p = 30 kPa

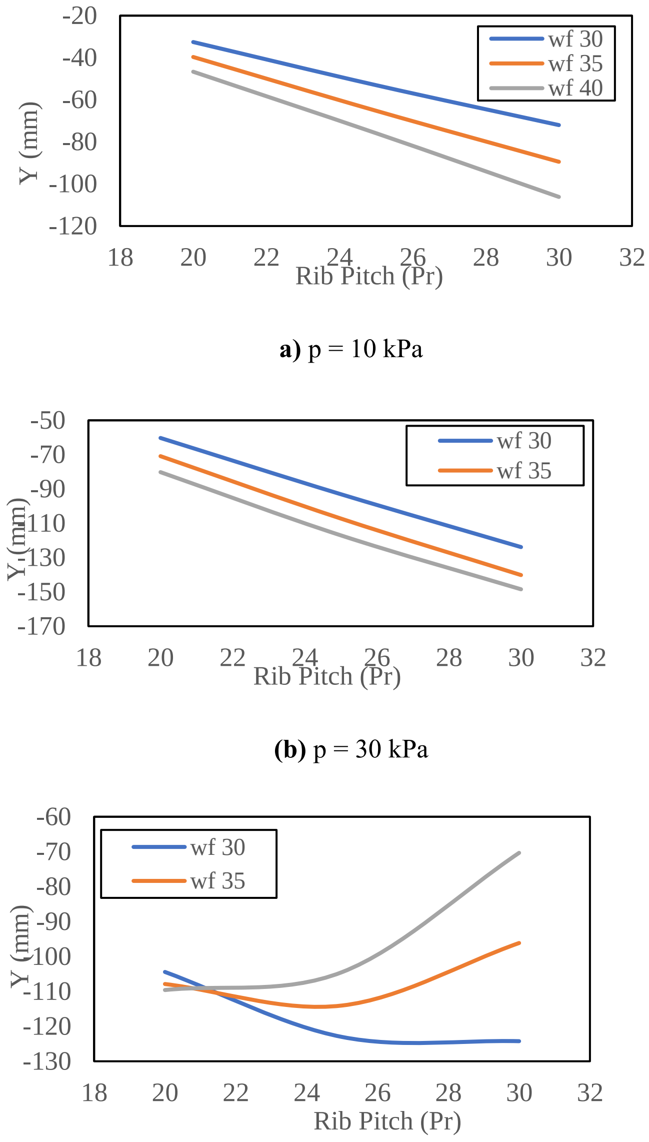


(c) p = 50 kPa

Fig. 6: Influence of Variation of Pneumatic Pressure, Rib Pitch, and Finger Width X-Axis Deflection of the Soft Gripper

4.3. Deflection on Y-axis (Y)

The analysis of the experimental findings uncovers a noteworthy trend in the deflection behavior along the Y-axis of the Soft Gripper. The graphical representation in **Fig. 7** illustrates a distinct pattern exhibited by the deflection curve on the Y-axis. Initially, the curve's minimum and maximum deflection points demonstrate a descending trend followed by an ascending trajectory. This unique behavior can be attributed to the soft gripper surpassing a rotation angle beyond 180° during its operational cycle. Notably, an increase in the pneumatic pressure (p), rib pitch (P_r), finger width (w_f) and lead to an upward deflection along the negative side of the Y-axis. Analysis of the dataset reveals a significant range in Y-axis deflection, varying from 32.55 mm to 148.45 mm. These findings also underscore the substantial influence of P_r, w_f, and p on the deflection behavior of the soft gripper along the Y-axis, elucidating its ability to execute intricate and versatile motions in response to modifications in these parameters.



a) p = 10 kPa

(b) p = 30 kPa

(c) p = 50 kPa

Fig. 7: Influence of variation of Pneumatic Pressure, Rib Pitch, and Finger Width on Y-Axis Deflection of the Soft Gripper

The simulation results provide valuable insights into the influence of working pressure (p) and parameter variations, specifically the rib pitch (P_r), finger width (w_f) and consequently the length of the finger (L), on both the actuator morphology and actuator performance of the soft gripper, particularly in the context of precise agriculture. These parameters play a crucial role in determining the final position of the gripping finger as well as regulating the deflection angle (Ø) and the deflection along the X- and Y-axes of the gripper, making them relevant to the development of advanced grippers in agriculture. It is from evident simulation results that changes in P_r, w_f, and p directly impact the positioning of the gripping finger, thereby shaping the actuator morphology of the soft gripper for agricultural applications. Adjustments in these parameters lead to varying deflection degrees, affecting the gripper's overall behavior and structure. The deflection angle (Ø) of the soft gripper, a key aspect of its actuator performance in the agricultural domain, is particularly influenced by the interplay between working pressure p and P_r, w_f pairs. Modifying these parameters can resulting in significant changes in Ø, ultimately impacting the gripper's ability to achieve precise gripping and manipulation tasks required in agriculture.

Furthermore, the deflection of the soft gripper along the X- and Y-axes, critical measures of its actuator performance in agricultural scenarios, is influenced also by working pressure p and P_r, w_f pairs. Specifically, an increase in P_r, w_f, as well as the application of higher pneumatic pressure, contributes to an increase in the deflection along these axes, enabling the gripper to adapt to various agricultural objects and handle them with precision. In contrast, the deflection on the Y-axis demonstrates a unique behavior characterized by a descending and ascending trajectory, allowing the gripper to maneuver in complex agricultural environments. Understanding the intricate relationship between P_r, w_f, and p and their impact on the gripping finger's position, deflection angle (Ø), and deflection along the X- and Y-axes is crucial for designing and optimizing both the actuator morphology and actuator performance of the soft gripper for effective use in precision agriculture. These findings provide valuable insights for further enhancing grippers' control, functionality, and overall performance in agriculture, empowering them to contribute to advancements in agricultural automation and robotic systems.

SUMMARY AND CONCLUSIONS

This study presents a design of pneu-net actuators capable of generating a wide range of deflections by modifying structural parameters. The impact of parameter changes on the actuators' deflection was extensively simulated using ANSYS finite element analysis (FEA). The FEA calculations included the evaluation of deflection angle and deflection along the X-axis and Y-axis under varying pressures ranging from 10 kPa to 50 kPa. The finger-width was adjusted from 30 mm to 40 mm with a 5 mm step, and the rib pitch was varied from 20 mm to 30 mm with a 5 mm step. The results revealed a consistent trend wherein increased finger width and rib pitch led to higher deflection angles and deflections along the X and Y axes, particularly when accompanied by increased pressure. The analysis demonstrated that the rib pitch (P_r) variation exerted the most significant influence on the bending angle for each applied pressure value (p). Moreover, increasing the finger width (w_f) or the gripper pressure (p) substantially increased the bending angle. The effect of pressure variation was found to have a greater impact than changes in finger width. Consequently, pressure variation proved more suitable for achieving significant adjustments in the bending angle, while variations in finger width allowed for finer modifications.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the mechatronics material Labs of the mechanical Engineering Department, Faculty of Engineering at Shubra, Benha University, Greater Cairo, Egypt.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

REFERENCES

[1] Zhang H., Kumar A. S., Chen F., Fuh J. Y. H., & Wang M. Y., (2019). "Topology optimized multimaterial soft fingers for applications on grippers, rehabilitation, and artificial hands,". *IEEE/ASME Transactions on Mechatronics*, *24*(1), 120-131. https://doi.org/10.1109/TMECH.2018.2874067

[2] Yang Y. and Chen Y., (2018), "Innovative Design of Embedded Pressure and Position Sensors for Soft Actuators, " IEEE Robotics and Automation Letters, 3(2), 656–663. https://doi.org/10.1109/LRA.2017.2779542

[3] Park W., Seo S., and Bae J., (2019), "A Hybrid Gripper with Soft Material and Rigid Structures," *IEEE Robot Autom Lett*, vol. 4(1), 65–72. https://doi.org/10.1109/LRA.2018.2878972

[4] Bao G. *et al.*, (2018), "Soft Robotics: Academic Insights and Perspectives Through Bibliometric Analysis," *Soft Robot*, 5(3), 229–24. https://doi.org/10.1089/soro.2017.0135

[5] Yang F. *et al.*, (2020), "Design and Optimize of a Novel Segmented Soft Pneumatic Actuator," *IEEE Access*, vol. 8, 122304–122313. https://doi.org/10.1109/ACCESS.2020.3006865

[6] Youssef S. M., Soliman M., Saleh M. A., Mousa M. A., Elsamanty M., and Radwan A. G., (2022) "Modeling of Soft Pneumatic Actuators with Different Orientation Angles Using Echo State Networks for Irregular Time Series Data," *Micromachines (Basel)*, 13(2), 216, https://doi.org/10.3390/mi13020216

[7] Li Y., Chen Y., and Li Y., (2018), "Distributed Design of Passive Particle Jamming Based Soft Grippers, " 2018 *IEEE International Conference on Soft Robotics (RoboSoft)*, , Livorno, Italy, 547–552. https://doi.org/10.1109/ROBOSOFT.2018.8405383

[8] Eduardo Navas, et al., (2021), "Soft Grippers for Automatic Crop Harvesting: A Review, " *Sensors, 21*(8), 2689. https://doi.org/10.3390/s21082689

[9] Wang X. et al., (2023), "Development and Evaluation of a Robust Soft Robotic Gripper for Apple Harvesting," Computers and Electronics in Agriculture, 204. https://doi.org/10.1016/j.compag.2022.107552

[10] Li Y., Chen Y., and Li Y., (2019), "Pre-Charged Pneumatic Soft Gripper With Closed-Loop Control," IEEE Robot and Automation Letters, 4(2), 1402–1408. https://doi.org/10.1109/LRA.2019.2895877

[11] Li Y., Chen Y., Yang Y., and Li Y., (2019), "Soft Robotic Grippers Based on Particle Transmission," *IEEE/ASME Transactions on Mechatronics*, 24(3), 969–978. https://doi.org/10.1109/TMECH.2019.2907045

[12] Birattari M. *et al.*, (2019), "Automatic Off-Line Design of Robot Swarms: A Manifesto," *Front Robot AI*, vol. 6. https://doi.org/10.3389/frobt.2019.00059

[13] Y. Li, Y. Chen, and Y. Li, (2018), "Distributed Design of Passive Particle Jamming based soft grippers," *2018 IEEE International Conference on Soft Robotics, RoboSoft*, 547–552. https://doi.org/10.1109/ROBOSOFT.2018.8405383

[14] Glick P., Suresh S. A., Ruffatto D., Cutkosky M., Tolley M. T., and Parness A., (2018), " A Soft Robotic Gripper with Gecko-Inspired Adhesive," IEEE Robotics and Automation Letters, 3(2), 903–910. https://doi.org/10.1109/LRA.2018.2792688

[15] Soliman M., Saleh M. A., Mousa M. A., Elsamanty M., and Radwan A. G., (2021), "Theoretical and Experimental Investigation Study of Data Driven Work Envelope Modelling for 3D Printed Soft Pneumatic Actuators," *Sensor & Actuators A: Physical*, vol. 331, 112978. https://doi.org/10.1016/j.sna.2021.112978

[16] Yang F. *et al.*, (2020), "Design and Optimize of a Novel Segmented Soft Pneumatic Actuator," *IEEE Access*, vol. 8, 122304–122313. https://doi.org/10.1109/ACCESS.2020.3006865

[17] Drotman D., Ishida M., Jadhav S., and Tolley M. T., (2019),"Application-Driven Design of Soft, 3-D Printed, Pneumatic Actuators with Bellows," *IEEE/ASME Transactions on Mechatronics*, 24(1), 78–87, https://doi.org/10.1109/TMECH.2018.2879299

[18] Park W., Seo S., and Bae J., (2019), "A Hybrid Gripper with Soft Material and Rigid Structures, IEEE Robotics and Automation Letters, 4(1), 65–72. https://doi.org/10.1109/LRA.2018.2878972

[19] Li Y., Chen Y., Ren T., Li Y., and Choi S. H., (2018), "Precharged Pneumatic Soft Actuators and Their Applications to Untethered Soft Robots," *Soft Robot*, 5(5), 567–575. https://doi.org/10.1089/soro.2017.0090

[20]https://www.diytrade.com/china/pd/20882276/Food_Grade_Liquid_Addition_Silicone_Rubber_For_Insole_Making.html