

Article

Optimal Design of 3D-Printed Flexible Fingers for Robotic Soft Gripping of Agricultural Products

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Abstract

Handling delicate agricultural products, such as tomatoes, requires careful attention from workers during harvesting, sorting, and packaging processes. This labor-intensive approach is often inefficient and susceptible to human error. A potential solution to improve efficiency is the development of automated systems capable of replacing manual labor. However, such systems face significant challenges due to the irregular shapes and fragility of these products, requiring specialized adaptable and soft gripping mechanisms. In this context, this paper introduces a parametric design methodology for 3D-printed flexible fingers in soft grippers, tailored for agricultural applications. The approach was tested in a case study that targeted soft agricultural products with diameters between 45 and 75 mm. Three finger topologies were modeled and compared to identify an optimal configuration. A prototype was then developed using 3D printing with Z-SemiFlex. Experimental tests confirmed that the prototype could grasp different fruits reliably and without surface damage. It achieved an Average Precision (AP) of 87.5% for tomatoes and 92.5% for mandarins across 80 trials. These results validate the feasibility of the proposed design methodology for fingers in soft grippers.

Keywords: soft gripper design; compliant gripping; soft robotics; smart agriculture; automated harvesting



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1. Introduction

The increasing demand for food production, combined with a declining agricultural workforce, climate change phenomena and an increase in water scarcity have forced the agriculture sector around the globe to develop new initiatives that aim to provide alternative solutions for farmers in their daily work [1,2]. Autonomous technologies are playing an important role in supporting emerging trends in the sector. These include precise agriculture, smart agriculture, vertical farming and circular agriculture [3,4]. These new initiatives require custom-tailored systems that could provide the necessary specific solutions to optimize resource usage and ensure sustainable and efficient agricultural practices [5,6]. An important direction in the proposed changes is the use of robotic systems that could provide aid in planting, nurturing, harvesting and manipulation of the plants and their fruits. For example, in the harvesting process, the use of autonomous robots that could replace manual labor shows increased interest [7]. Given the specialized nature of these tasks, the design of new robotic systems must carefully consider specific operational parameters [8,9]. A systematic approach is needed, involving the comparison of different design options, refinement of structures, and prototype testing to ensure that the final

solutions meet the specific needs of agricultural applications [10]. Soft robotics, a branch of robotics focused on developing machines and devices from flexible, compliant materials, has shown promising results in the field [11,12]. Particular attention has been given to soft grippers, which are designed to handle delicate crops with precision during harvesting, sorting, and packaging processes [13–16].

As presented by Shintake et al. in [17], soft grippers can be categorized into three main classes: actuation-based gripping, variable stiffness gripping, and adhesion-based gripping, each with distinct functioning principles and applications. Of the three technologies, actuation-based gripping is the most widely used soft gripper category in agriculture, relying on pneumatic, hydraulic, mechanical or tendon-driven mechanisms to deform and wrap around manipulated objects. These grippers are particularly effective for handling delicate fruits and vegetables without causing damage [17].

Different finger topologies are used to develop actuation-based compliant soft grippers, ranging from controlled deformable bellows to compliant mechanical structures that change their shapes and grasp the manipulated object due to the external actuation [17,18]. This paper focuses on the grippers that are based on compliant mechanisms. These types of finger structures offer increased performance with a simplified manufacturing process that has lower production costs in comparison with other gripper solutions. An example of an actuation-based compliant gripper is presented by Xie et al. in [19], who developed a soft gripper composed of silicone fingers designed for fruit-picking robots. In the design process of the fingers, the authors proposed a method that focuses on topology optimization by taking into account the contact behavior and stress constraints to achieve optimal performance. Another example of such a gripper is proposed by Liu et al. in [20]. In their paper, the authors proposed a two-finger underactuated gripper design based on monolithic compliant fingers synthesized through topology optimization. The finger geometry was generated using a strain-energy-based objective function that balances geometric and mechanical advantages, enabling the finger to deform elastically and adapt to the shape of various products.

Another particular topology of this type of gripper is the soft grippers based on the fin-ray principle [21–23]. The shape of the gripper fingers is inspired by fish fins, and they are designed so that they passively adapt to the handled object when actuated. An example in this direction is the gripper developed by Shin et al. in [24]. In their paper, the proposed gripper is optimized by adjusting parameters such as the rib number and slope angles to enhance its flexibility and grip strength. An et al. [25] proposed such a soft robotic gripper for tomato harvesting which integrates a compliant fin-ray finger with a passive four-bar linkage-based cutting mechanism, enabling adaptive grasping and stem cutting without requiring multiple actuators. The design process employed a pseudo-rigid body modeling combined with Finite Element Analysis (FEA) to optimize the finger geometry for uniform force distribution and minimal mismatch with the surface of the fruit.

As can be observed in the literature, the geometry of the compliant mechanism (fingers) that compose the soft gripper directly influences the grasping process of the manipulated product. The parameters that should be addressed in the design phase of such a system takes into account the displacement, deformation of the element in contact with the product and the applied force on the product. These parameters are important elements that must be optimized in the design process ensuring proper grasping within predefine limits concerning deformation and grasping force.

Taking into account the above statements, the paper proposes a method for designing flexible fingers for soft grippers, with application in agriculture, using a parametric design approach. The proposed methodology takes into account the geometry of the manipulated product, deformation behavior and the maximum applied force. The design process consid-

ers an initial rigid linkage mechanism that is further used to define parametrized models for compliant fingers of the gripper which are further optimized using FEA. The method is tested for a case study that aimed to develop a soft gripper capable of handling irregularly shaped objects with diameters ranging from 45 to 75 mm. Three gripper topologies were analyzed, and FEA in Ansys was employed to identify the optimal geometric configuration. A prototype was then developed using Z-SemiFlex produced by Zortrax (Poland), a flexible material chosen for its mechanical properties, to validate the simulation results.

The paper is structured as follows. Section 2 presents the parametric design approach used to design the compliant fingers of the gripper. In Section 3, the simulation results are analyzed and the optimal finger topology is identified. Taking into account the result obtained for the optimal topology, a gripper system was developed and tested; the obtained experimental results are presented in Section 4. Finally, the paper ends with the conclusions.

2. Flexible Finger Topology Optimization

The use of compliant mechanisms in designing gripper fingers offers several advantages over the traditional rigid-body mechanisms. Motion in compliant mechanisms results from the elastic deformation of their components, eliminating the need for joints, which reduces parts count, friction and the need for lubrication [26]. Although this design approach introduces additional constraints, such as limited force output and complex deformation analysis, it offers significant benefits in terms of soft manipulation, adaptability, and the ability to adapt to the shape of the manipulated product [19].

The design process of such mechanisms differs from the standard linkage mechanism design and can take one of the following approaches: analytical modeling, numerical methods and topology optimization [27]. Analytical modelling is based on beam theory and the fundamental principles of material mechanics to predict the movement and deformation of the compliant mechanism elements [28]. This approach is particularly effective for simple and regular finger geometries, where assumptions regarding boundary conditions and stress distributions remain valid. Numerical methods, on the other hand, enable the simulation of more complex structures under predefined loads [29]. Using the FEA method, engineers can accurately analyze stress distributions and displacement of the gripper elements, even in non-linear or geometrically complex configurations. Topology optimization is a computational design strategy that generates the optimal material layout within a confined design space to obtain a desired mechanical performance. This approach often leads to innovative and non-intuitive compliant structures [30,31].

As an initial step, in the proposed design methodology, a gripper configuration is defined using rigid linkage mechanisms. This configuration serves as the starting point for the development of the finger's compliant mechanisms. These rigid-body systems offer well-understood kinematic behavior, making them suitable for initial geometry definition and constraint-driven optimization. For finger-based grippers, commonly employed linkage architectures include the four-bar linkage, slider-crank mechanism, rack-and-pinion systems, or cam and lever mechanisms [32].

Figure 1 presents two of the mentioned linkage mechanisms, each shown in relation to the manipulated object that, in this example, has a circular shape with a diameter d . From a design constraints perspective, several parameters must be considered to ensure effective grasping. Particularly the geometry of the mechanism, which must enable the fingertip to follow a precise trajectory that guarantees stable and tangential contact with the object's surface. This trajectory is typically defined by parameters such as the linkage lengths, joint angles, and contact radius.

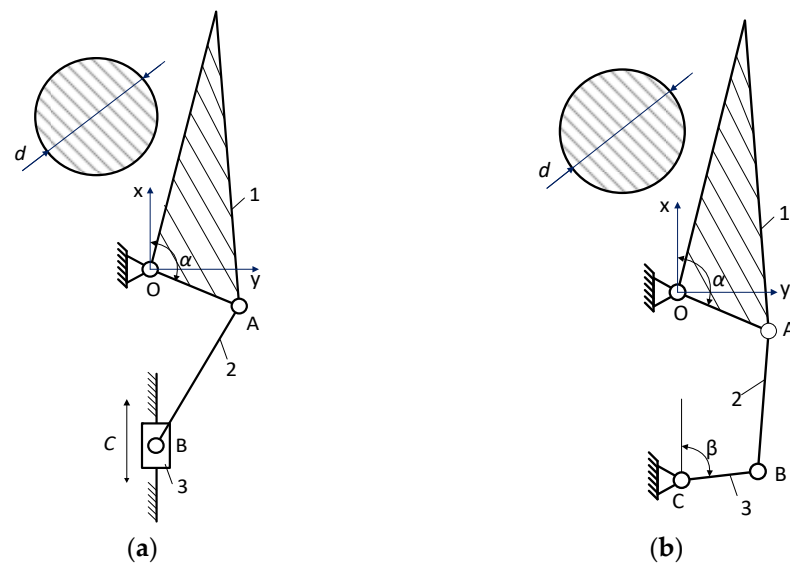


Figure 1. Schematics of linkage mechanisms used in the design of the gripper's fingers (a) slider-crank mechanism (b) four-bar mechanism.

In the case of the slider-crank and four-bar mechanisms, the kinematics and kinetostatics of the mechanism are directly influenced by the link lengths and the input received from the actuator (displacement c and angle β respectively). The synthesis of the mechanism must ensure that the orientation angle α , in both mechanisms, changes so that the finger reaches the desired contact point without approaching singular configurations. In the two configurations, the finger's geometry, actuation range, and joint placement must be calculated in relation to the diameter of the target product d , ensuring secure and repeatable grasping performance.

The rigid linkage mechanism is further utilized to define the geometry of the compliant mechanism, as shown in Figure 2. While the compliant mechanism exhibits a similar overall behavior to the initial rigid design, differences appear due to the elasticity of its structural elements. To evaluate the deformation resulting from actuator input and interaction with the manipulated object, FEA is employed.

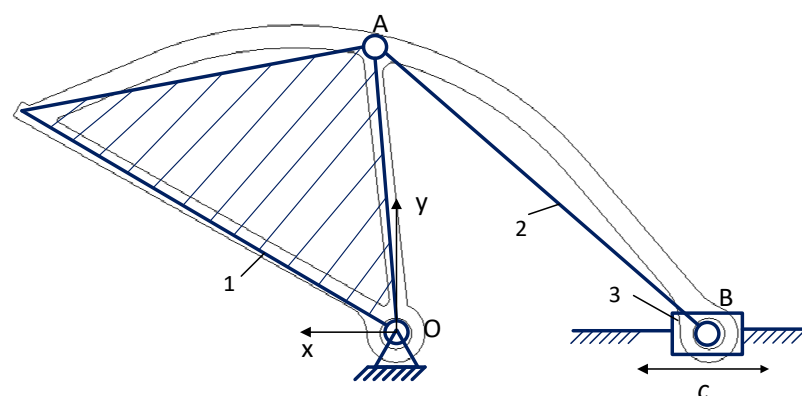


Figure 2. Defining the initial shape of the compliant mechanism.

For accurate FEA simulation results, precise material properties are required. Given that the gripper finger is fabricated using additive manufacturing, its mechanical behavior can vary depending on specific printing parameters. Therefore, the material properties are experimentally determined using a universal testing machine. In these tests, tensile force and elongation are measured, and tensile (Engineering) stress-strain curves are determined and then converted to true stress-true strain for the FEA simulations. Using the test results,

material behavior can be represented using various models: linear, multilinear, visco-elastic, hyper-elastic, etc.

An example of a cross-section of a test specimen in the slicing software is presented in Figure 3. The test specimen is designed in accordance with the standard ISO 527-2 [33] for such testing procedures. The specimens were manufactured using a Zortrax M300 3D printer produced by Zortrax (Poland) with Z-SemiFlex material. Printing parameters included a 0.4 mm nozzle, 0.2 mm layer thickness, an extruder temperature of 235 °C, and a 30% honeycomb infill pattern. The honeycomb structure was selected because it provides an excellent balance between material usage and the mechanical strength and isotropy, ensuring that the printed parts exhibit uniform performance under multi-directional loading conditions.

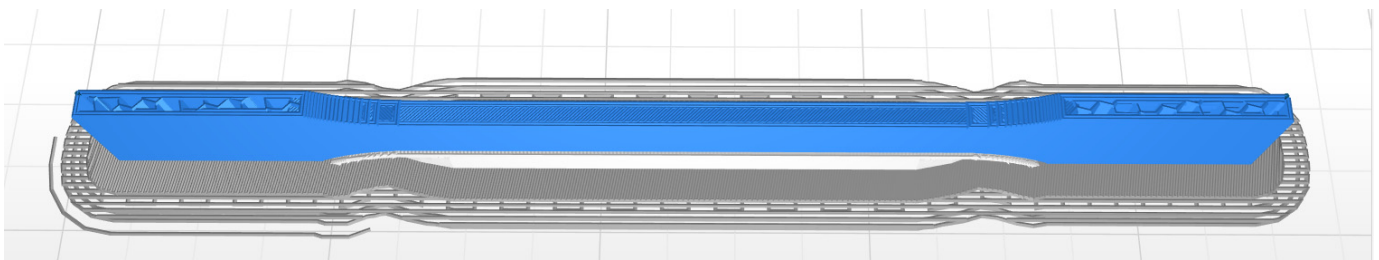


Figure 3. Section of the testing probe with an infill of 30% and a honeycomb pattern.

The FEA is further used to optimize the geometry of the proposed compliant mechanism. The optimization aims to identify a finger geometry that maximizes the displacement and ensures good adaptation and contact with the manipulated object. For this, the geometry of the compliant mechanism is defined using a set of p_i $\{i = 1 \dots n\}$ parameters. The number n of the parameters depends on the number of geometrical elements of the gripper that could change during the optimization process. Figure 4 presents an example of a parametrized gripper finger. The design of the fingers is implemented in Design Modeler from Ansys, which allows the creation of parametrized models.

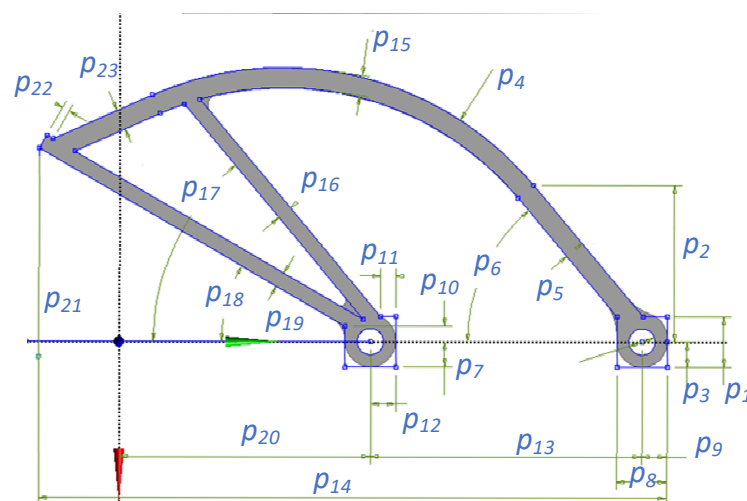


Figure 4. Parametrized model of the gripper finger.

Using Ansys Workbench—Static Structural analysis, several parameters p_j $\{j \leq n\}$ can be selected to be modified in predefined ranges. The method enables the analysis to be run with different sets of values for the geometric dimensions (e.g., arm length, relative orientations, wall thickness or hole diameter), facilitating the generation and analysis of different configurations. Based on the selected parameters and their predefined ranges,

the FEA provides the designer with results that estimate the finger deformation in terms of displacements for different points of interest, equivalent stresses, actuation force and contact force (Figure 5). The FEA simulation can also be used to visualize the finger deformation in contact with different-shaped objects, as shown in Figure 5b, where the arrow represents the reaction force on the contact surface.

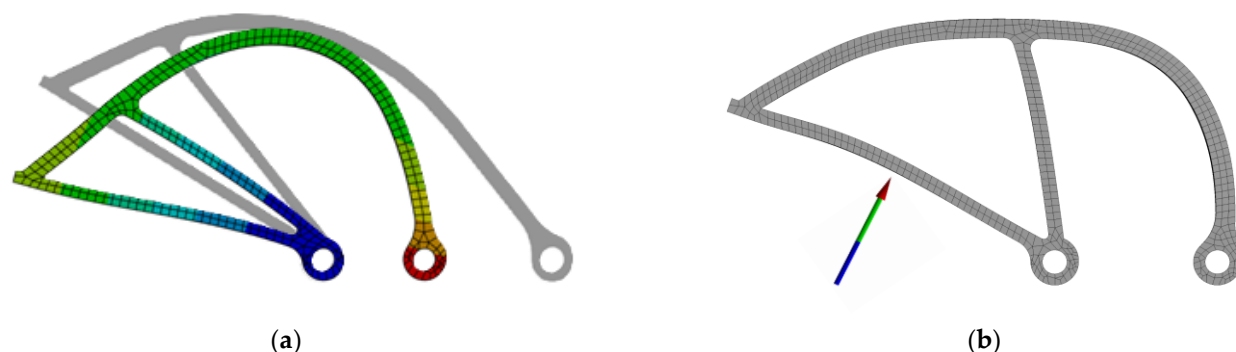


Figure 5. Output of the simulation (a) displacement simulation (b) simulation with contact.

The proposed method facilitates the execution of a wide range of simulations that evaluate how variations in finger topology influence finger deformation and the grasping process. By analyzing the simulation results across the defined parameter space, the designer can identify the geometry that best satisfies the imposed design requirements.

3. Case Study and Numerical Results

Using the proposed method, three different finger topologies were tested to evaluate their suitability for harvesting soft fruits/vegetables, such as tomatoes. The diameter of the manipulated objects can vary between $d_{min} = 45$ to $d_{max} = 75$ mm and can support a grasping force that varies in the range of 1 to 5.5 N, with an optimal target around 2.75 N [34].

3.1. Analyzed Finger Topologies

The input parameters in the method are the minimum and maximum diameters d_{min} & d_{max} of the manipulated products, the actuator maximum displacement c_{max} (for the slider crank mechanism), or the variation of angle β (β_{min} and β_{max}) together with the l_3 length (for the four-bar mechanism). The output parameters are the length of the mechanism elements (l_1 and l_2), eccentricity e and contact length l_c .

In this case study, the rigid-body linkage selected as the starting point for the design is a slider–crank mechanism, as shown in Figure 6. The objective is to determine the optimal values of the link lengths l_1 , l_2 , and l_c that enable effective manipulation of products within a predefined size range.

The minimum and maximum diameters d_{min}/d_{max} of the manipulated products influence the overall dimension of the gripper. Starting from these values, the l_c length, eccentricity $e = 0.9 d_{min}/2$ and the angles α_{min} and α_{max} are calculated.

The required contact-surface length between the finger and the manipulated object (that is assumed to have a circular geometry) can be scaled linearly with the object diameter under a constant-curvature contact assumption (this value is calculated for the product with the maximum diameter). Based on the contact mechanics model proposed by Hao et al. [35] and the constant-curvature formulation in [36], the length l_c can be expressed as a sum of the contact surface length and a design constant:

$$l_c = \frac{\Theta \cdot d_{max}}{2} + C \quad (1)$$

where d_{max} is the object's diameter, Θ (in radians, per finger) is the wrap angle (portion of the object's circumference that is in contact with the finger) and C is a design constant that accounts for additional design requirements beyond the pure contact length. The value of Θ depends on the gripper design. For two-finger grippers, each finger must cover a larger portion of the object to maintain a stable grasp, so typically Θ ranges from 2.1 to 3.1 rad. For three-finger grippers, the contact arc is smaller and can approach a minimal configuration corresponding to three-point contact, but typically Θ ranges from 1.05 to 1.57 rad. The constant C is determined during the design process as the sum of three components: $C = C_{tip} + C_{radius} + C_{tolerance}$, where C_{tip} ensures a minimum clearance gap between the fingertip and the object at maximum opening, enabling reliable release; C_{radius} provides the extra length required for the finger to achieve the desired wrap angle around the object; and $C_{tolerance}$ covers specific manufacturing and assembling constraints. In this work, C was determined as 25.8 mm based on design allowances, including tip clearance, wrap-angle feasibility, and geometric constraints of the gripper.

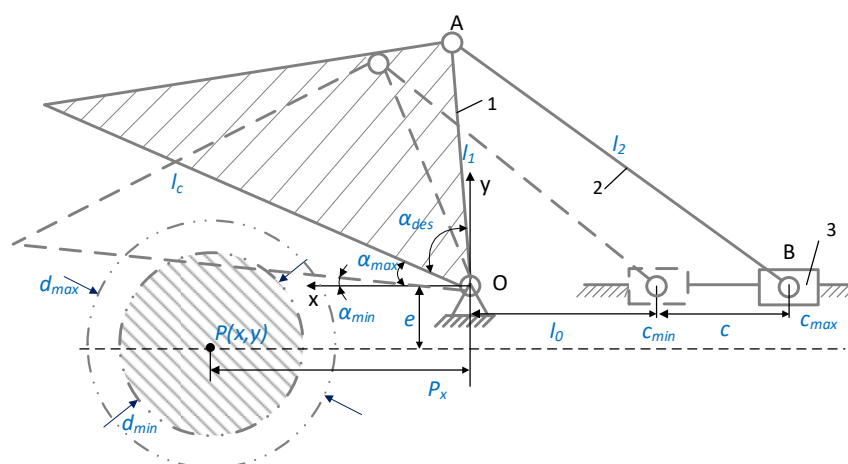


Figure 6. Schematics of the rigid-body linkage.

The angles α_{min} and α_{max} depend on the product position relative to the gripper P_x and its radius r , where $r \in \{d_{min}/2, d_{max}/2\}$. Taking into account that the value of P_x should satisfy $P_x \leq l_c - r$, the two angles can be calculated using Equation (2).

$$\alpha_{(min/max)} = \arctan \left(\frac{r \sqrt{P_x^2 + e^2 - r^2} - e P_x}{P_x^2 - r^2} \right) \quad (2)$$

For the given dimensions, the values for the two angles are $\alpha_{min} = 2.5$ deg and $\alpha_{max} = 26.1$ deg. To account for operational tolerances, a safety factor of 1.3 is applied: α_{min} is decreased to ensure proper grasp of small products ($\alpha_{minsf} = 1.9$ deg), and α_{max} is increased to ensure proper release of larger products ($\alpha_{maxsf} = 33.9$). To analyze the kinematics of the mechanism, α_{des} is also considered; this is a design angle that characterizes the initial geometry of linkage 1, which in this case is $\alpha_{des} = 54$ deg.

The kinematic dependency between the orientation of linkage 1 (defined by α) and the displacement c of slider B is defined by Equation (3). Using the equation and imposing the values for fully closed configurations ($\alpha = \alpha_{minsf} + \alpha_{des} = 55.9$ deg associated with $c_{min} = 0$ mm) and fully open configurations ($\alpha = \alpha_{maxsf} + \alpha_{des} = 87.9$ deg associated with $c_{max} = 20$ mm), the lengths l_1 and l_2 can be calculated.

$$l_1^2 + (l_0 + c)^2 - l_2^2 - 2l_1(l_0 + c)\cos\left(\frac{\pi}{2} - \alpha\right) = 0 \quad (3)$$

By introducing the two configurations in Equation (3), a nonlinear system of equations is obtained with the unknowns l_1 and l_2 . Solving the system of equations, the values presented in Table 1 were obtained.

Table 1. Parameters that define the rigid-body mechanisms.

Parameter	Description	Value	Measurement Unit
l_0	Base offset between joints	34	mm
l_1	Length of link 1	75.98	mm
l_2	Length of link 2	51.51	mm
l_c	Contact length of the finger	75	mm
c_{min}/c_{max}	Min./Max. slider displacement	0/20	mm
Θ	Wrap angle around the object	1.31	rad
C	Design adjustment constant	25.8	mm

Based on the geometric values from Table 1, three topologies for the compliant finger mechanism were defined. These configurations are presented in Figure 7. Two of the configurations include a single reinforcement element, while the third has a dual-reinforcement design. Model 1 includes a single reinforcement element (Figure 7a). In this case, the analysis (in the optimization process) is performed on angle A55, defined as the orientation of the reinforcement element relative to the Ox-axis of the finger. During simulation, the angle A55 varies from initial α with +40 deg down to -30 deg, using a 10 deg step and near the maximum displacement the resolution was increased to 1 deg. In this case, it can be interpreted that the l_1 length of linkage 1 from the initial rigid-body linkage remains constant and the length of l_2 is varied.

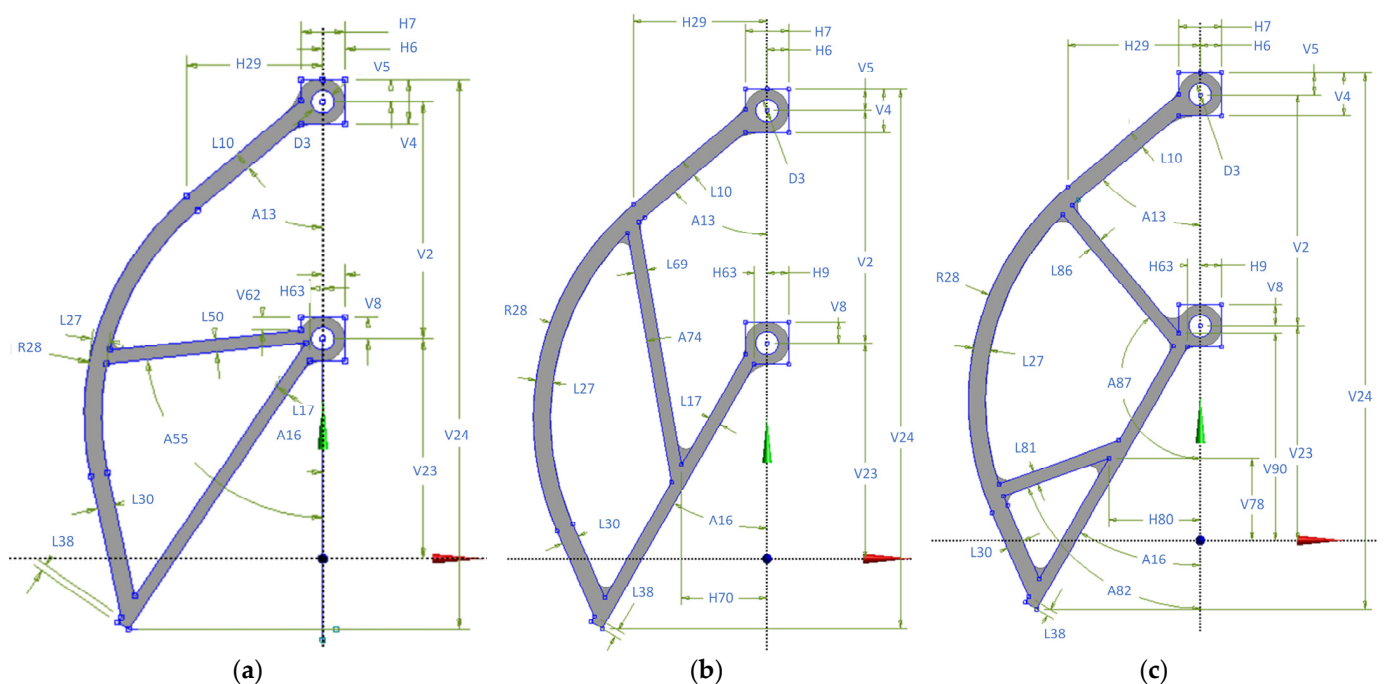


Figure 7. Gripper finger parametrized models (a) Model 1 (b) Model 2 (c) Model 3.

For Model 2, during simulation, the orientation of the reinforcement element is modified by repositioning it to the midpoint of the bar that forms the contact surface with the manipulated object (Figure 7b). In this configuration, the optimization focuses on parameter A74, which defines the angle of the reinforcement element relative to the Ox-axis. During the simulation, this angle is changed from 150 deg to 80 deg with predefined increments of

10 deg, around the maximum displacement the increment was reduced to 1 deg. In this case, both the l_1 and l_2 lengths on linkages 1 and 2 are modified.

Model 3 introduces a dual-reinforcement structure (Figure 7c). The design includes a longer and a shorter reinforcement element. In this configuration, the optimization focuses on two angles A87 and A82, both defined with respect to the Ox-axis of the finger. During the simulation, the parameter A87 varies in the range of 100 to 70 deg, and the parameter A82 varies in the range of 70 to 100 deg, both with an increment of 10 deg. In this case, the length of l_2 and the stiffness of the linkage 1 is varied while the length l_1 of linkage 1 remains constant.

3.2. Material Properties

The compliant fingers are manufactured through 3D printing using Z-SemiFlex from Zortrax, a thermoplastic elastomer (TPE) that is characterized by elastic properties. Due to the layered manufacturing process and infill pattern, the resulting structure behaves as a non-homogeneous material, exhibiting a nonlinear deformation response that is strongly influenced by the printing parameters. To accurately simulate this behavior, the material response to tensile stress was identified. In compliance with ISO 527-1, which specifies a minimum of five specimens for statistical reliability, five tensile tests were carried out on samples printed using the printer settings detailed in Section 2. The tests were performed using an Instron 3360 machine.

During the simulation of the three fingers' topologies, the stress level remained below 3.41 MPa. The experimental True Stress–True Strain curve (Figure 8) shows that, within this low-stress range, the material behaves linearly elastic. Therefore, a linear elastic model was used for simulation, with a Young's modulus of 53.86 MPa derived from the experimental data, with a standard deviation of 2.58. The obtained yield strength was 4.06 MPa with a standard deviation of 0.17, represented on the stress-strain curves in Figure 8 with a black triangle.

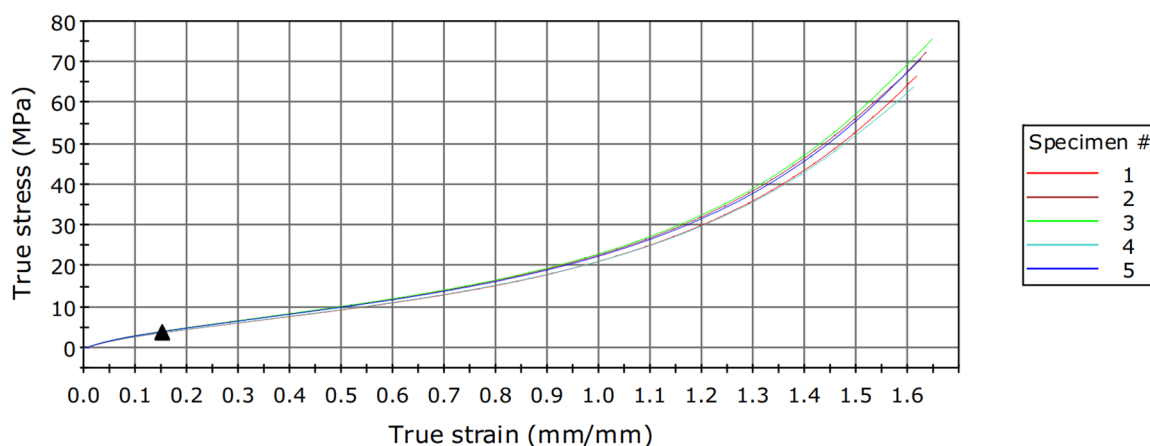


Figure 8. True stress-strain curve for Zortrax's Z-SemiFlex with 30% infill.

3.3. Simulation Results

The first objective of the simulation was to identify, for the given three finger configurations, the parameter sets that achieve maximum tip displacement.

For Model 1, the parametric analysis showed that the maximum tip displacement is 25.39 mm and occurs at A55 = 84 deg, requiring an actuation force of 4.02 N. The variation of displacement with respect to angle A55 is presented in Figure 9a. The gripper finger deformation for A55 = 84 deg, in comparison to its initial undeformed state, is presented in Figure 9b.

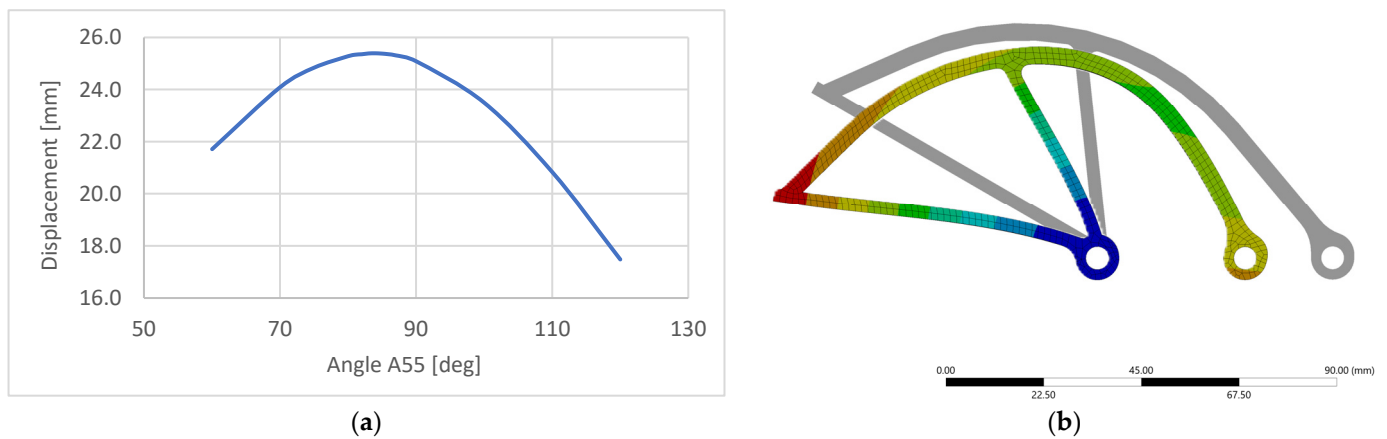


Figure 9. Simulation results of finger Model 1 (a) displacement variation of the fingertip (b) finger displacement for $A55 = 84$ deg.

For Model 2, the maximum tip displacement obtained in the parametric analysis is 22.72 mm at $A74 = 80$ deg, requiring an actuation force of 1.72 N. The variation of displacement in relation to the angle $A74$ is presented in Figure 10a. The gripper finger deformation for angle $A74 = 80$ deg, in comparison to its initial undeformed state, is shown in Figure 10b.

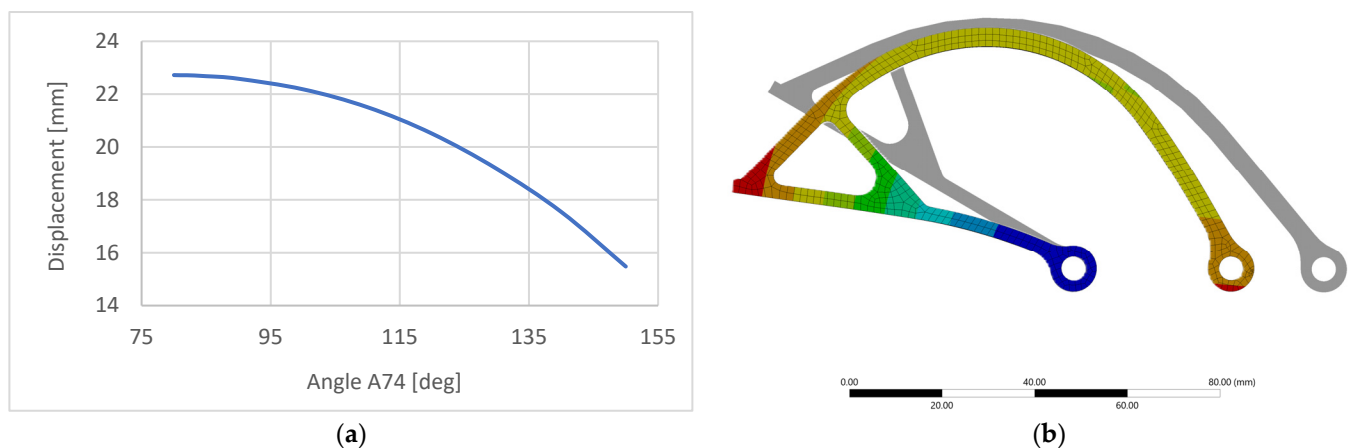


Figure 10. Simulation results of finger Model 2 (a) displacement variation of the fingertip (b) finger displacement for $A74 = 80$ deg.

For Model 3, the maximum tip displacement of 23.74 mm was obtained at angles $A82 = 70$ deg and $A87 = 88$ deg, requiring an actuation force of 4.23 N. The variation of displacement as a function of the two angular parameters is presented in Figure 11a. The gripper finger deformation for $A82 = 70$ deg and $A87 = 88$ deg, in comparison to its initial undeformed state, is shown in Figure 11b.

For all three models, the parametric analysis was conducted with an imposed displacement of 20 mm applied to the slider (joint B). As can be observed, the maximum (gripper) tip displacement of 25.39 mm is obtained using Model 1.

Next, the behavior of the three models in their maximum-displacement configurations was analyzed during contact with a deformable object. The object was modeled with a stiffness of 5 N/mm to simulate the grasping process of a soft fruit, which deforms by approximately 1 mm under a 500 g load. The force required to move the mobile platform by the same 20 mm was evaluated. The values obtained for the three configurations are presented in Table 2.

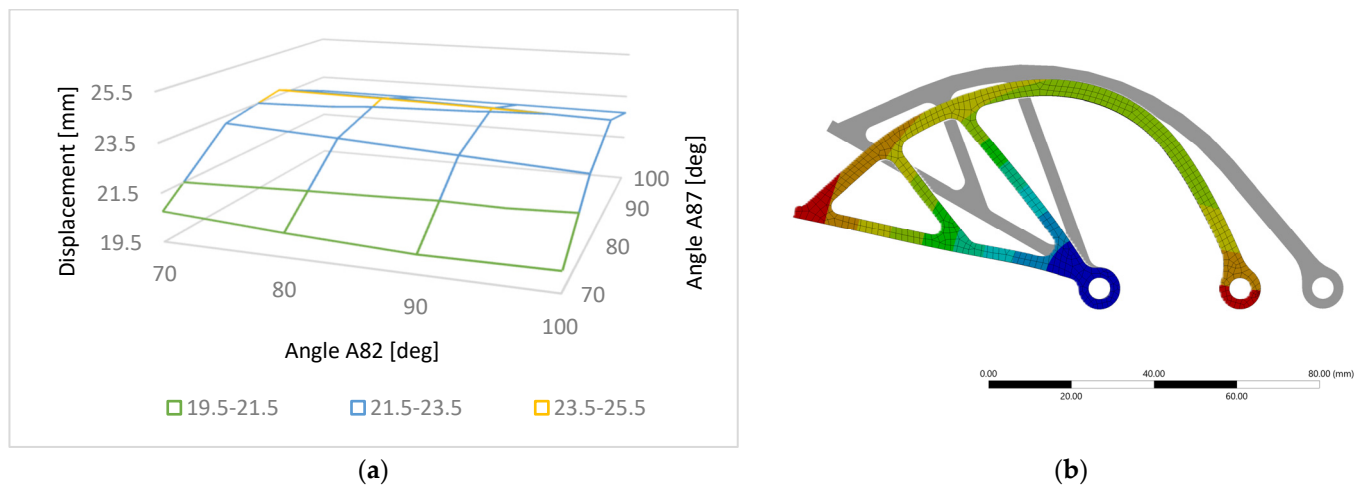


Figure 11. Simulation results of finger Model 3. (a) Displacement variation of the finger tip; (b) finger displacement for A82 = 70 deg and A87 = 88 deg.

Table 2. Simulation results for actuation force and stress.

	Actuation Force [N]	Equivalent Stress [MPa]
Model 1	12.41	3.41
Model 2	3.58	1.61
Model 3	11.09	3.12

The deformation of the Model 1 finger, as a result of the actuator movement and contact force with the manipulated object, is presented in Figure 12.

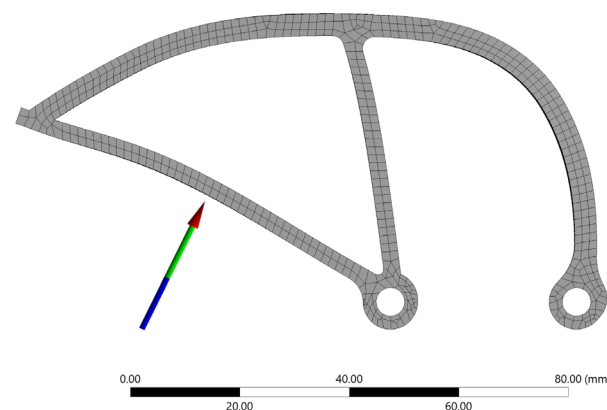


Figure 12. Elastic deformation of Model 1 during contact with a simulated soft fruit.

3.4. Simulation Data Analysis

Based on the simulation results obtained in the previous subsection, the following can be concluded:

- Model 1 provided the largest fingertip displacement, reaching 25.39 mm for a 20 mm actuator stroke. This wide deformation range makes it the most adaptable when handling objects of different sizes. The drawback is that it demands the highest actuation force of 12.41 N and also shows the greatest stress level of 3.41 MPa when in contact with a soft object;
- Model 2, in contrast, is highly energy-efficient. It requires only 3.58 N of force, much less than the other models, and has the lowest stress of 1.61 MPa. These values make it ideal for low-power applications. Its main drawback is the reduced fingertip

displacement of 22.72 mm, which restricts the gripper's range and makes it less adaptable to smaller fruits;

- Model 3 offers balanced performance in comparison with the first two models. With a displacement of 23.74 mm and improved stability from its dual-reinforcement design, it ensures a more consistent grip and potentially better stiffness control for precision tasks. In this case, the actuation force required was 11.09 N, similar to Model 1, and had the equivalent stress of 3.12 MPa.

The optimal choice depends on the goal. Model 1 offers the best adaptability and grasping range, Model 2 excels in energy efficiency and low stress, and Model 3 provides balanced performance. For this study, Model 1 was selected for its superior grasping capability and adaptability. To make the selection process more consistent and less subjective, a weighted performance score can be used. In this method, criteria are normalized and then combined into a single overall score for each model.

4. Experimental Results

For testing purposes, the first proposed topology (Model 1) was further used in the gripper prototyping phase. The gripper prototype was fabricated using a combination of 3D-printed components and off-the-shelf elements for the actuation system, enabling straightforward prototyping and scalability. The components were manufactured with a Zortrax M300 3D printer. The fingers, requiring compliance, were produced from approximately 75 g of Z-Semi-Flex filament using the print settings detailed in Section 2, while the remaining structural parts were printed in ABS (Figure 13).

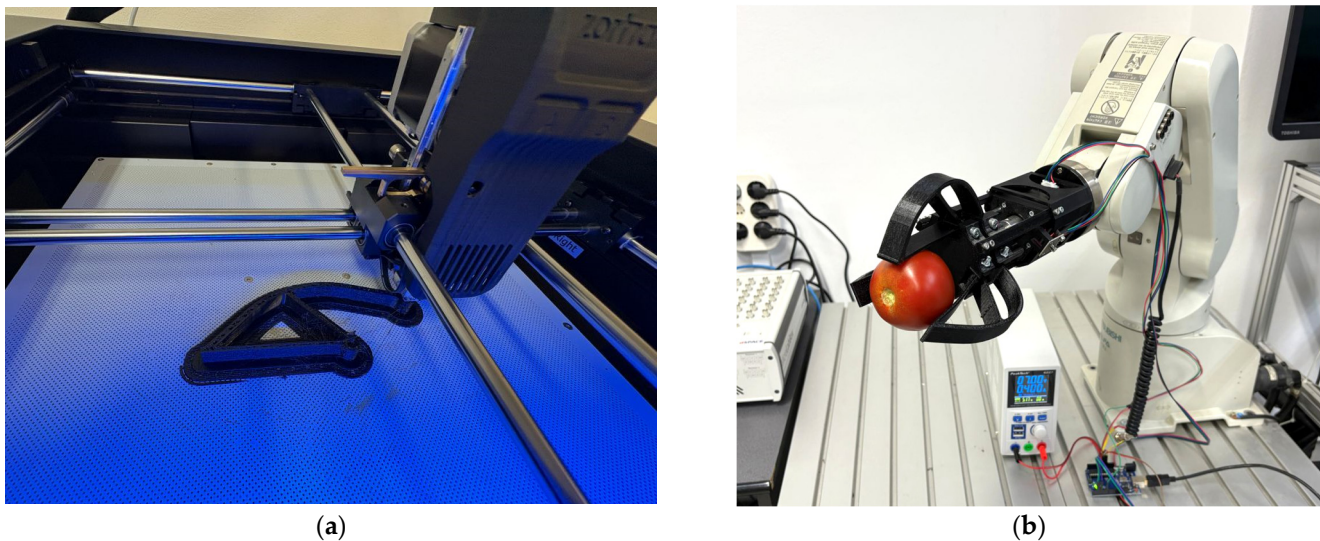


Figure 13. Experimental setup (a) finger printing process (b) gripper prototype.

The gripper consists of two platforms: a fixed platform and a mobile platform. The three fingers are connected to both platforms in a triangular configuration, which facilitates the grasping of spherical or irregularly shaped objects. The actuation of the mobile platform is implemented using a stepper motor that transmits the movement to the mobile platform through a trapezoidal screw. The entire gripper assembly is connected to the Mitsubishi RV-2AJ robot (Figure 13b).

The developed tests aimed to validate the results of FEA simulation. The experiments were carried out under stable laboratory conditions, where temperature and humidity remained constant, minimizing potential environmental influences on the results.

The first test aimed to measure the displacement of the tip of the compliant finger under a no-load condition. The test was performed for an actuator displacement of 20 mm,

replicating the conditions in the FEA simulation. The deformation was quantified using an image-based measurement technique, illustrated in Figure 14. For this, two high-resolution images were captured in the fully open configuration and the fully closed configuration. The analysis was conducted along the vertical axis (Oy), which corresponds to the primary direction of finger displacement during grasping. Key reference points were manually identified on the captured images and used to measure pixel distances along the Oy -axis. Calibration was performed using a known length in the scene, allowing for the pixel-to-millimeter conversion factor to be established. Using this calibrated scale, the displacement of the fingertip in the Oy direction was measured. For the Model 1 finger, a displacement of 24.1 mm was measured. The relative error between the simulated and experimental Oy -axis displacement of the fingertip, corresponding to a 20 mm actuator movement, is 5.08%. Due to the elasticity of the element for the 20 mm actuation, the resulting angle $\alpha_{\text{exp}} = 14.1$ deg is larger than the necessary α_{minsf} . To compensate for this, the actuator movement must be increased. It was observed that $\alpha_{\text{minsf}} = 1.9$ deg is obtained for an actuator movement of 25.5 mm.

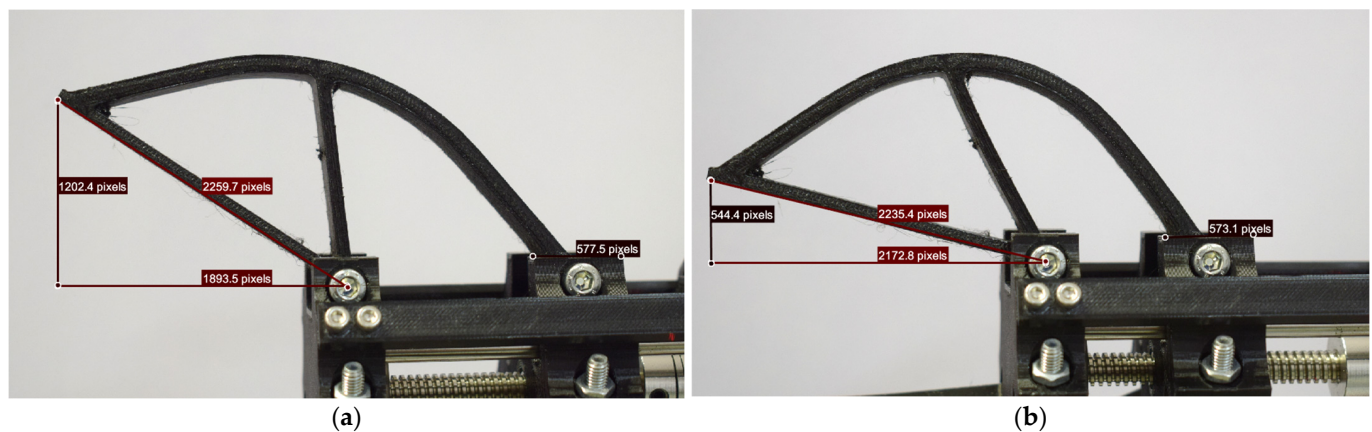


Figure 14. Experimental setup—finger deformation analysis (a) fully open configuration (b) fully closed configuration.

Next, the gripper was tested for grasping agricultural products: tomatoes and mandarins. The sample products were selected to meet predefined specifications, considering variations in shape, weight, hardness, and adhesion across the groups. Within each group, specimens of small, medium, and large sizes were included to evaluate the gripper's adaptability to changes in geometry, weight, and firmness. To minimize the potential influence of the robot arm-induced stiffness and residual forces, the grasp process was carried out with a fixed end-effector pose. During the grasp, the force was generated only by the gripper's internal actuation while the robot provided only pose constraint.

For the tomatoes, 4 different diameter products were used in the test, ranging from 49.5 mm to 68.5 mm (Figure 15). The weights of each product were 0.07 kg, 0.095 kg, 0.14 kg, and 0.178 kg.

For the mandarins, 4 different diameter products were used in the test, ranging from 54 mm to 73.5 mm (Figure 16). The weights of each product were 0.075 kg, 0.101 kg, 0.149 kg, and 0.164 kg.

For each product, a total of 10 grasping attempts were performed. The AP scores achieved were 87.5% for tomatoes and 92.5% for mandarins. The high AP score demonstrates the gripper's consistent and reliable performance across both product types. Slippage occurred in only a small number of trials, 5 out of 40 for tomatoes and 3 out of 40 for mandarins, and no damage was caused to any of the manipulated products. In the suc-

cessful gripping attempts, the gripping process was steady, and the elastic fingers changed their shape to adapt to the geometry of the manipulated part.

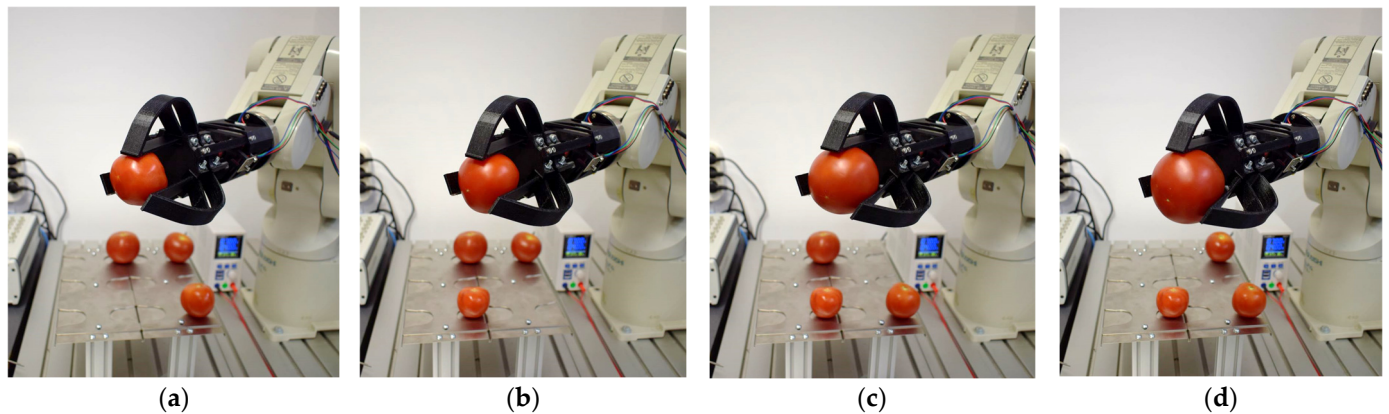


Figure 15. Experimental results—handling tomatoes (a) $d = 49.5$ mm (b) $d = 57.2$ mm (c) $d = 64.4$ mm (d) $d = 68.5$ mm.

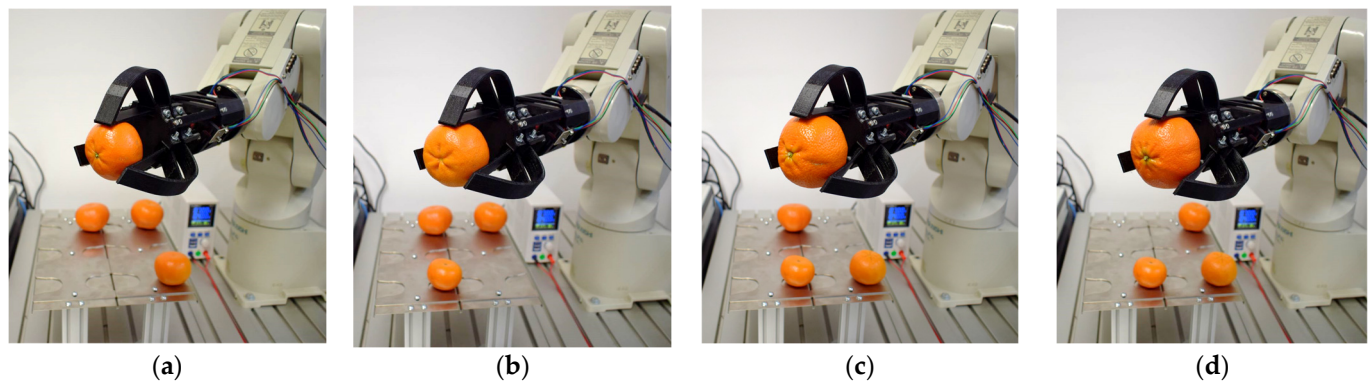


Figure 16. Experimental results—handling mandarins (a) $d = 54$ mm (b) $d = 60.5$ mm (c) $d = 67.9$ mm (d) $d = 73.5$ mm.

The experimental results confirmed the initial hypotheses, showing that the developed gripper can reliably grasp and adapt to products of varying diameters within the tested range and different weights. These findings validate the proposed design concept.

5. Conclusions

This paper proposed a parametric design methodology for 3D-printed compliant fingers used in soft robotic grippers for handling delicate agricultural products. By combining classical rigid-body kinematics with FEA and experimentally derived material properties, the method enables simulation-driven optimization of finger geometries to meet displacement, contact force, and mechanical reliability requirements.

Three finger topologies were designed and evaluated using this method. From the three models, Model 1 demonstrated the best performance, achieving a tip displacement of 25.39 mm under a 20 mm actuator stroke. The prototype exhibited only a 5.08% error in displacement compared to FEA results, validating the simulation-driven design.

The gripper prototype successfully handled products with diameters between 49.5 mm and 73.5 mm, such as tomatoes and mandarins, without causing any visible surface damage. The AP scores were 87.5% for tomatoes and 92.5% for mandarins, with 8 slippage events out of 80 trials, demonstrating a high level of reliability and repeatability in handling delicate products.

The proposed solution provides an alternative to fin-ray and tendon-based designs, offering monolithic compliant fingers that focus on adaptability, simplified fabrication, and ease of manufacturing without the need for complex actuation systems.

Future work will focus on extending the methodology to dynamic grasping across a broader range of operating conditions. Another key direction will be the integration of force and tactile sensors, which would allow the gripper to operate with precise closed-loop control. The methodology can be adapted for other soft robotic applications requiring compliant, adaptive gripping.

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Abbreviations

The following abbreviations are used in this manuscript:

FEA	Finite Element Analysis
TPE	Thermoplastic elastomer
AP	Average Precision

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