

Soft Robotics for Advanced Handling of Delicate Fruit Products

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Keywords: Soft Robotic Grippers, Soft Grippers, TPU 60A, TPU 95A, Flexible Materials, Delicate Handling, Fin Ray Effect, FRE, Robotics, Grippers.

Abstract: Soft robotic grippers can be an effective tool for handling sensitive and irregularly shaped objects, such as horticultural products. This study evaluates three soft gripper designs—Straight, Constant Curve, and Beak—fabricated using Thermoplastic Polyurethane (TPU) with shore hardness 60A and 95A. The grippers were produced using a 3D printer and tested on a universal testing machine to assess mechanical performance. Practical tests revealed that the Beak gripper made with TPU 60A exhibited superior performance, achieving a peak force of 10.59 N at a displacement of 21.65 mm, making it suitable for delicate tasks like handling fruits, without causing damage. In contrast, grippers made with TPU 95A, while possessing higher force capacities, were excessively rigid and risked damaging delicate items. The study shows the importance of material selection and gripper design in optimizing performance for specific applications. The findings validate simulation data and indicate that TPU 60A is more appropriate for applications requiring gentle handling. Future work includes testing with objects of varying shapes, conducting fatigue tests, and exploring multi-material gripper designs with embedded sensing capabilities to enhance adaptability and control during use.

1 INTRODUCTION

Grippers, like robots themselves, are fundamental elements in the modern industry, since the manipulation of objects with various shapes is one of the most common and complex challenges in the field of robotics (Youn, 2020). To meet the tasks of handling sensitive products or those with complex geometries, soft grippers have been developed. They are made from flexible materials, allowing considerable deformation to adjust to the product without damaging it. These grippers enable superior results when handling sensitive and irregular objects,

compared to grippers made from more rigid materials (Dinakaran, 2008). With advances in technologies such as additive manufacturing and more flexible materials, soft grippers have become a more viable, adaptable, and affordable solution. These advances have allowed these grippers to be used more widely, providing a simple, economical, and effective approach to dealing with complex tasks such as safe interaction with humans and handling fragile objects (Zhai, 2023).

The fragility, sensitivity, stickiness, and slipperiness of most food and agricultural products have fuelled the development of soft robotic grippers

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that are deformable, flexible, safe, low-cost, and environmentally friendly (Liu, 2023). Thermoplastic Polyurethane (TPU) is a thermoplastic elastomer bridging the gap between rubbers and plastics. It combines high flexibility and durability (Hasan, 2022), is widely available in a broad range of Shore hardness values and exhibits excellent mechanical strength. TPU is also readily available as a feedstock material for Fused Filament Fabrication (FFF) Additive Manufacturing (AM), making it suitable for the production of soft robotic grippers.

(He, 2023) developed a rigid-soft coupled robotic gripper for adaptable grasping. The experimental results showed that the proposed gripper can adapt to objects with different properties (shape, size, weight, and softness) and hold them steadily. The feasibility of the design procedure was confirmed, as well as the compliant and dexterous grasping capabilities of the developed gripper. (Zapciu, 2017) developed an adaptive robotic end effector-that used 3D printed Fin Ray Effect (FRE) Soft Robotic Gripper Fingers (SRGF) with embedded conductive 3D-printed sensing circuits, which gave the end-effector capacitive touch sensing and bend sensing capabilities for manipulation of sensitive objects such as fruits and vegetables.

The development of a robotic gripper for agricultural robots must consider several factors, such as the type of crop and its physical characteristics, such as the shape, size, and sensitivity of the fruit or vegetable. For example, the grippers need to be adaptable enough to handle fragile items without damaging them, which is critical in crops such as tomatoes, apples and peaches. In addition, grippers must be designed to operate in unstructured agricultural environments, where variability in size and shape, as well as the presence of leaves and branches, can complicate the harvesting process. Technologies such as sensors and artificial intelligence algorithms can help the control of the gripping and handling tasks to optimise harvesting (Han, 2024), (Vrochidou, 2022).

In the case of flexible grippers, they have a significant capacity for deformation within the elastic regime. This ensures safe interaction with the environment and minimises the risk of damaging delicate objects. For this reason, these manipulators are often chosen as end effectors in agricultural robots for harvesting and sorting produce (Elfferich, 2022), (Wang, 2023) and (Williams, 2019).

Soft grippers that rely on the FRE present a simple economically viable approach to grasping objects of various shapes (Yao, 2024). The biomimetic structure eliminates the need for inbuilt actuation in the fingers,

thus facilitating passive adaptation to the surface of an object upon contact. Since the introduction of the FRE SRGF by Festo in 2016, extensive research has inspired numerous innovative applications.

Prior work has demonstrated agricultural use cases and flexible grasping with FRE-based soft grippers.

However, systematic, side-by-side evaluations of various rear-frame designs under the same materials and test conditions are still mainly missing. Our study fills this gap by comparing three geometries: Straight, Constant Curve, and Beak, fabricated in TPU 60A and TPU 95A using the identical Universal Testing Machine (UTM) process and object set, and by comparing the results with prior simulations. This approach identifies material hardness and rear-frame shape as the main design levers for the gentle handling of delicate fruit.

Building on previous characterization and computational simulation work (Lang, 2025), three distinct FRE SRGF models were designed and experimentally tested to evaluate the influence of two key parameters: the Shore hardness of TPU and the geometric shape of the finger's rear frame side. The tested geometric configurations included Straight, Constant Curve, and Beak-shaped designs. The results provide clear guidance: the TPU 60A Beak achieves the best balance of compliance and force, whereas TPU 95A is often too rigid for fragile produce. We further link mechanics to outcome by relating observed slippage/marking to the measured force-displacement response and contact evolution, and we show agreement with simulations, strengthening actionable design rules for horticulture and food-handling applications.

2 MATERIALS AND METHODS

The FRE SRGF design process was founded on a simplified analysis of the structural elements of a FRE SRGF, as described by Antunes (2024a) and shown in Figure 1. This approach involved evaluating the static force distributions across a segmented model of the FRE SRGF, allowing a clearer understanding of the mechanical role of each component.

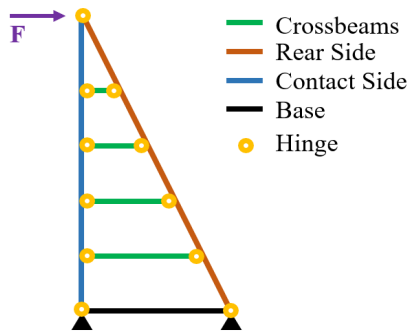


Figure 1: Simplified representation of an FRE SRF with a grasping force at the tip of the finger.

The material selected for this study was Filaflex TPU in both 60A and 95A Shore hardnesses, produced by Recreus Industries S.L. The chosen 3D printer was the Artillery Sidewinder X1, shown in Figure 2, because it was validated and recommended by the filament manufacturer for printing these TPU filaments (Recreus Industries S.L., 2024). This contributed to achieving consistent print quality, given the challenges associated with FFF AM of highly flexible materials.

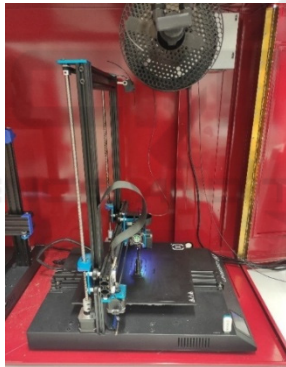


Figure 2: 3D printer Artillery Sidewinder X1.



Figure 3: Shimadzu Autograph AGS-X-50 kN (Shimadzu Corporation, 2023).

The Precision Universal Tester Autograph AGS-X-50 kN (Shimadzu Corporation, 2023) is shown in Figure 3 and was used to carry out the tensile tests. It features a reading resolution of 0.001 mm and a sampling rate up to 1000 Hz (1ms). It is equipped with TRAPEZIUM LITE X software to control tests in real time and generate reports. (Shimadzu Corporation, 2023).

The UR3e collaborative robot, shown in Figure 4, is widely used for small-scale assembly tasks and handling small objects (Universal Robots, 2024). The use of this model, together with the actuator Robotiq 2F-85 Adaptive Gripper (Robotiq, 2020) was used, and it allows enough customizability to adapt and attach different types of gripper fingers. This flexibility enabled testing with various SRGF, focusing on handling delicate products, such as fruit, to assess their suitability in gentle handling applications.

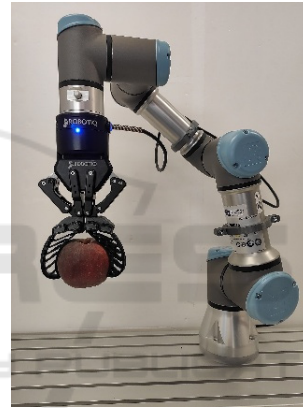


Figure 4: Cobot UR3e gripping a peach with the developed FRE SRGF.

The three FRE SRGF models were designed using Computer-Aided Design (CAD) based on the design developed by Antunes (2024a) and Antunes (2024b), as shown in Figure 5 were printed in TPU 60A and 95A. The printing orientation followed the procedure based on (Lang, 2025).

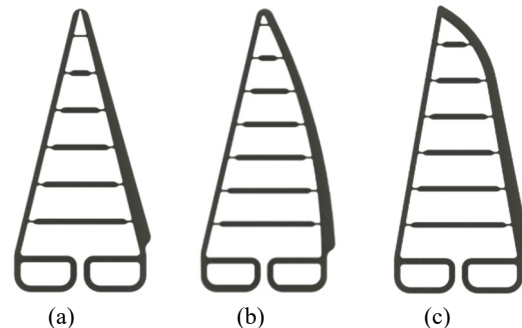


Figure 5: Three FRE SRGF CADs: (a) *Straight*. (b) *Constant Curve*. (c) *Beak*.

To carry out the practical tests, a mechanism developed in Antunes (2024a) and Antunes (2024b), shown in Figure 6, was used. This allowed attaching the SRGF to the Shimadzu Autograph AGS-X-50 kN, and the control of the gripping width for grasping the object shown in Figure 7.

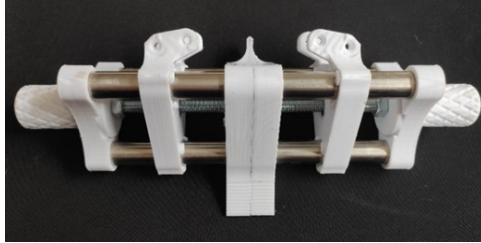


Figure 6: Mechanism for the base and being able to carry out practical tests.



Figure 7: Cylinder for carrying out the practical test.

3 RESULTS AND DISCUSSIONS

Practical tests were performed on a UTM with a built-in load cell while the crosshead imposed a prescribed finger-spacing trajectory. Each trial mounted two identical fingers on the parallel mechanism and grasped a rigid cylinder centred between them. The measured force is the total normal gripping force transmitted through the cylinder; under symmetric contact, the per-finger force $\approx$ total force/2. Force-displacement curves Figures 11, 12 and 13 were derived directly from the UTM signal, using the same displacement limit as in the simulations.

8 tests were carried out with each SRGF design, 5 of which were valid. For each test, each gripper model was mounted on the mechanism developed to carry out the tests, and the cylinder was aligned in the centre so that both grips had the contact face area as close as possible. Figure 8 shows the process of carrying out the first valid test on the Straight model, where (a) is the start of the test, (b) is the point where the maximum force occurs and (c) is the end of the

test, the same occurs for Constant Curve in Figure 9, and for Beak in Figure 10.

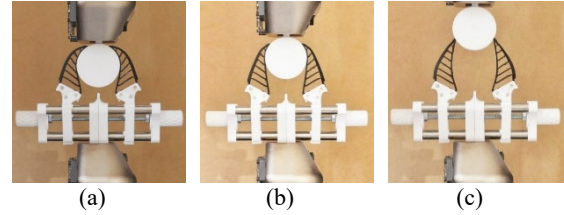


Figure 8: First Practical Test – Straight: (a) Beginning, (b) Maximum Force; (c) End.

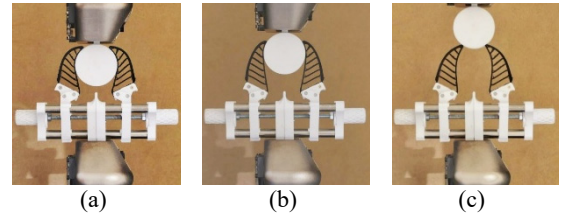


Figure 9: First Practical Test – Constant Curve: (a) Beginning, (b) Maximum Force; (c) End.

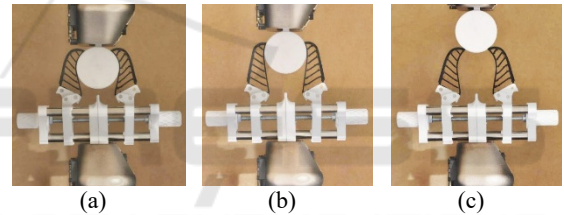


Figure 10: First Practical Test – Constant Curve: (a) Beginning, (b) Maximum Force; (c) End.

In the case of the Straight SRGF design, it can be seen in Figure 11 that the maximum forces reached were between 5.87 N and 6.69 N, with an average of 6.3 N and a standard deviation of 0.82. All cases were considered until 50 mm of displacement was reached, as occurred in the computer simulations.

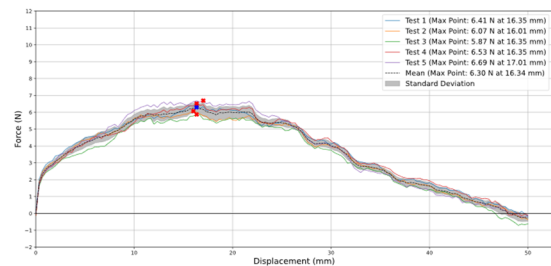


Figure 11: Valid Practical Tests - Straight.

The Constant Curve SRGF design results are shown in Figure 12, the forces ranged from 9.67 N to 11.13 N, with an average of 10.37 N. These tests also

considered up to 50 mm of displacement. It should be noted that this model has a higher standard deviation (1.46), as the range of force values achieved was also greater.

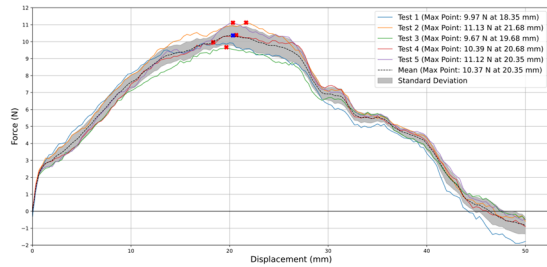


Figure 12: Valid Practical Tests – Constant Curve.

In the case of the results obtained for the Beak SRGF design seen in Figure 13, the forces obtained in the tests were between 10.48 N and 10.9 N, with a standard deviation of 0.53 and an average of 10.59 N, the highest of all the gripper models tested.

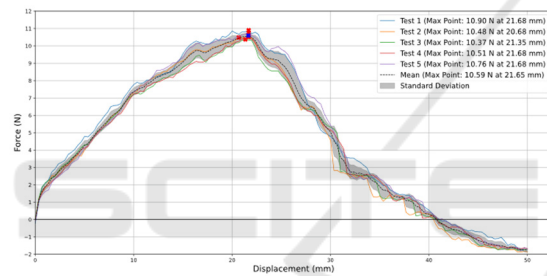


Figure 13: Valid Practical Tests – Beak.

Figure 14 shows the average of the Straight, Constant Curve, and Beak SRGF designs tested. It should be noted that the Beak SRGF design is the one with the best result, followed by the Constant Curve SRGF design and then the Straight SRGF design. Due to the design developed, the Beak SRGF design, after reaching the maximum point in terms of force, the contact area of this design decreases, as the object is only held at the top tips of the grippers, and therefore ends up having an abrupt drop until the end of the test.

Analysing Figure 14, it is important to note that all the designs showed negative forces towards the end of the tests. This condition occurred since, when they reached around 50 mm of displacement, the object slipped and the grippers now under the object were pushing it away, i.e., in compression rather than traction. This behaviour indicates that, after a critical point of displacement, the gripper is no longer effective in supporting elongation, resulting in a reversal of the applied force.

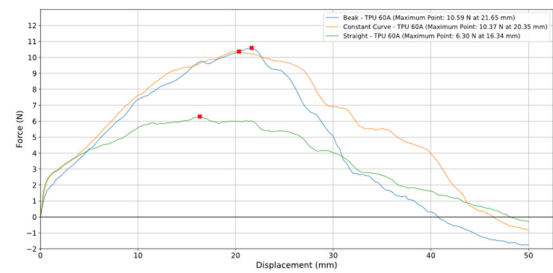


Figure 14: Average of the practical tests of the three gripper designs.

This regime transition is particularly noticeable in the Beak SRGF design and Constant Curve SRGF design, which reached the highest force values but also experienced the sharpest drop. The Straight SRGF design, showed a lower peak force, although it also showed relative stability in its behaviour until the end of the test.

3.1 Comparison of Practical Grip Results Between TPU 60A and TPU 95A

Testing and comparing the results of the SRGF designs made from TPU 60A and TPU 95A in practical tests allows for the practical understanding of the mechanical behaviour of these materials in their applications, such as handling fruit or delicate objects. According to Antunes (2024a) and Antunes (2024b), TPU 95A was chosen due to its favourable balance of flexibility and mechanical strength.

Analysing Figure 15 and Table 1, the grippers made with TPU95A can in fact apply a higher maximum force before the object slips compared to those made with TPU60A, reaching 72 N for the Beak gripper, 58 N for the Constant Curve and almost 48 N for the Straight gripper. These values are very high, but this rigidity can be excessive for applications that require a softer handling, such as fruit handling.

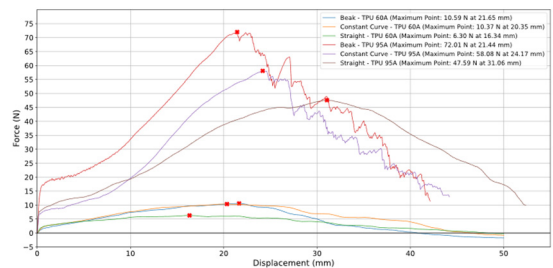


Figure 15: Grippers made of TPU 60A vs. TPU95A.

Table 1: Comparison of maximum force values before slipping between grippers produced with TPU60A and TPU95A.

Grippers	Maximum Force (TPU 60A) [N]	Maximum Force (TPU 95A) [N]
Beak	10.59	72.01
Constant Curve	10.37	58.08
Straight	6.30	47.59

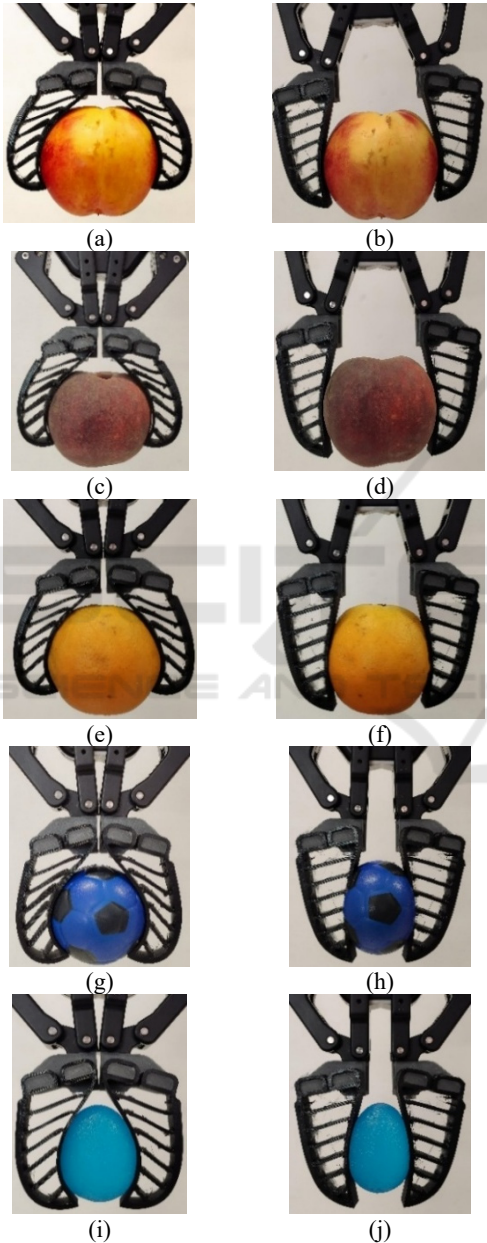
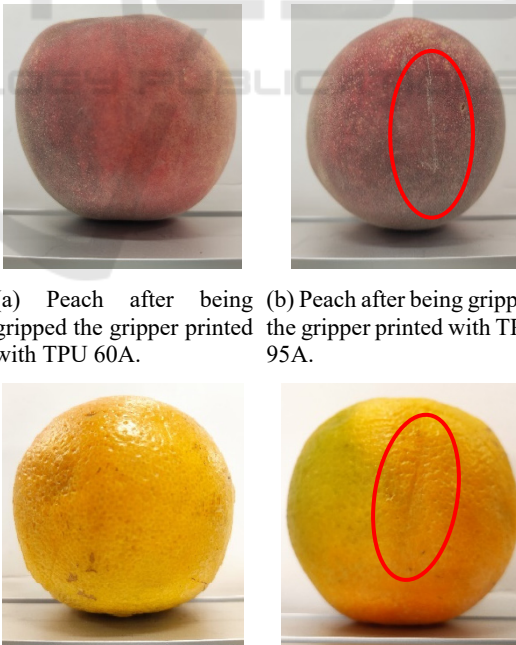


Figure 16: Beak gripper when picking up different objects: (a) TPU60A- Nectarine. (b) TPU95A- Nectarine. (c) TPU60A- Peach. (d) TPU95A- Peach. (e) TPU60A- Orange. (f) TPU95A- Orange. (g) TPU60A- Soft Football. (h) TPU95A- Soft Football. (i) TPU60A- Flexible Ball. (j) TPU95A- Flexible Ball.

For this reason, although TPU 60A exhibits lower resistance to deformation and a reduced maximum gripping force before slippage, its greater flexibility results in improved force distribution over the surface of the grasped fruits (peaches, oranges, and apples) with an average weight of 185 g. Given the relatively low weight of these fruits, the maximum gripping forces provided by TPU 60A remain sufficient for reliable manipulation, ensuring gentle handling without causing damage, while still providing adequate durability for continuous use.

This condition can be seen in Figure 16 (a), (c), (e), (g), and (i), where the Beak gripper printed with TPU60A was tested by gripping a series of objects. Figure 16 (b), (d), (f), (h), and (j) are for the same objects, but the test was carried out with the Beak gripper printed with TPU 95A. These figures test the best-performing SRGF developed in a laboratory environment when handling a variety of objects, with a focus on fruit or fruit-like shapes.

Figure 17 (a), (b), (c), and (d) show the effect of gripping the Beak grippers printed on TPU 60A and TPU 95A. The gripper made with TPU 95A is more rigid and stiff, leaving visible marks on the fruit. In contrast, the fruit gripped with the gripper printed on TPU 60A showed no visible damage, demonstrating a softer grip suitable for delicate handling.



(a) Peach after being gripped the gripper printed with TPU 60A. (b) Peach after being gripped the gripper printed with TPU 95A.

(c) Orange after being gripped the gripper printed with TPU 60A. (d) Orange after being gripped the gripper printed with TPU 95A.

Figure 17: Peach and Orange after being gripped by the Beak gripper printed with TPU60A and TPU95A.

4 CONCLUSIONS

Besides the practical tests used a rigid cylinder and a small set of fruits. Tests were quasi-static with a specific printer/material brand and printing orientation, which was already tested (Lang, 2025). The setup assessed a parallel two-finger grasp without closed-loop sensing/control, but do not diminish the central finding that TPU 60A Beak provides a favourable compliance–durability trade-off for delicate handling.

The practical tests indicated that the Beak gripper performed best in terms of force capacity, followed by the Constant Curve and then the Straight grippers. The Beak gripper achieved a maximum force before slippage of 10.59 N at a displacement of 21.65 mm, demonstrating superior load-bearing capability. The Constant Curve gripper closely followed with a maximum force before slippage of 10.37 N at 20.35 mm, suggesting that its design is nearly as effective as the Beak gripper. In contrast, the Straight gripper reached a lower maximum force before slippage of all the designs with 6.30 N at 16.34 mm, implying that its less curved design is less efficient in supporting loads.

All grippers showed a marked decrease in force after reaching their maximum force before slippage values. Despite no visible signs of fractures or plastic deformation, future work should include fatigue tests to assess gripper durability under prolonged and cyclic use. It is also suggested that tests be carried out with objects of different shapes in addition to the cylinder used, broadening the scope of the practical evaluation and computer simulation; performing bruise-threshold quantification on representative produce to map allowable contact pressures; multi-material printing and embedded/skin sensing for closed-loop grip control; surface liners/textures and food-grade elastomers for hygienic wash-down.

These advances have the potential to add great value to companies by offering custom solutions at a lower associated cost.

Comparisons with grippers made from TPU95A, as designed by Antunes (2024a) and Antunes (2024b), revealed that, as expected, TPU95A offers greater resistance to deformation, its high hardness can compromise the integrity of delicate items like fruit during handling. Grippers made with TPU60A provide better adaptability by conforming to the object shapes without sacrificing durability or causing damage to the fruit, thus allowing delicate handling of soft and perishable products.

The experimental results offer insights into how the design of the frame's rear side of FRE SRGF and

material selection impact gripper efficiency during handling tasks.

ACKNOWLEDGEMENTS

These results are within the research activities of project “ROBOTA-SUDOE - Robotics, Automation, and Digitalization as Drivers of Competitiveness and Growth for SMEs” (S1/1.1/P0125), which is co-funded by the European Union through the European Regional Development Fund (ERDF) and national funds, under the territorial cooperation Interreg Europe Programme 2021–2027 (eSUDOE 2021–2027). This research was partially funded by the Portuguese Foundation for Science and Technology, I.P. (FCT, I.P.) FCT/MCTES through national funds (PIDDAC), under the R&D Unit C-MAST/Center for Mechanical and Aerospace Science and Technologies, reference: Projects UIDB/00151/2020 (<https://doi.org/10.54499/UIDB/00151/2020>) and UIDP/00151/2020 (<https://doi.org/10.54499/UIDP/00151/2020>)

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