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A gripper for delicate edible manipulation

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ABSTRACT

The general manipulation of delicate edible products requires of specific grippers able to firmly grasp these kind of products without damaging them. To address this problem we follow a soft and variable-stiffness approach. In this paper we design and construct successive gripper prototypes which fingers are composed of rigid and soft parts. The stiffness of the soft parts can be modified using the jamming principle. The gripper properties are experimentally evaluated using a subset of NIST benchmarks. This allows to obtain comparable and standardised results, used to improve the initial gripper design. In addition a new benchmark, the edible grasping benchmark, is proposed and used to measure the performance of the grippers while grasping fruits and vegetables. The final gripper prototype overcomes the problems observed in fruit and vegetable picking systems. It has been demonstrated in the experimental tests that the gripper has sufficient payload and adaptability to grasp several edibles without damage.

1. Introduction

Nowadays, Spain is the second country in Europe and the fifth in the world in terms of fruit and vegetable exportation, with a total value of $20.8B, which can be translated as the 6.1% of the total exports of the country [1].

The products, processed and exported from Spain such as oranges, citrus, cucumbers, melons, lettuce, etc., differ in size, shape and mechanical properties [2]. A robotic gripper for a warehouse where more than one type of this merchandise is stored should be able to adapt to the desired products regardless their shapes and properties.

The main objective of this research if to desing and enhance a gripper capable of grasping delicate objects as agri-food products. Fruits and vegetables need a gripper which can grasp them firmly to perform a pick and place, but also in a delicate and soft way so the products are not damaged. The gripper should also interact with hard and heavy fruits or vegetables. It should be able to perform adaptive and enveloping grasps without damaging the products but in a firm manner so it can lift heavy ones.

This paper presents a variable-stiffness gripper, shown in Fig. 1, able to change its stiffness depending on the phase and conditions of the grasping process. It is soft and adaptive when first touching the products, and rigid when the products need to be lifted and transported.

Fig. 1. Gripper proposed.

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The variable stiffness property is obtained by a combination of a rigid under-actuated finger structure that holds a soft pad which stiffness is changed by a jamming mechanism similar to the Universal Gripper approach [3]. The design, manufacture and improvement of this gripper is presented in this paper. To test and improve the gripper two benchmark tests sets are applied. The first one is an adaptation of four different NIST benchmarking protocols [4], the second one is a self-made test to demonstrate the functionality of the griper to manipulate soft and delicate objects without damage.

The paper is organised as follows. First of all, in Section 2 a literature research is done. In Section 3 the initial gripper design and the improved ones are shown and described. In the same section, the benchmarking tests that are applied to the gripper are also explained. The results of applying the tests are summarised in Section 4. Later on, the discussions extracted from the tests and results are argumented in Section 5. Finally, the paper conclusions are exposed in Section 6.

2. Related work

The stiffness of a gripper and that of its fingers is an important parameter for a successful grasping task. Grippers with stiff fingers deform less under high contact forces and are adequate for grasping heavy objects with a simple control. However, they have difficulties to cope with irregular and/or delicate objects, as fruit and vegetables, introducing also high contact pressures which can damage the product being grasped. It is one of the most important design criteria for mechanical components and systems. Recent works [3,5–10] [11,12] investigate grippers that can change their own stiffness at will, so that they can achieve more grasping capabilities or deploy different grasping forces depending on the object that they are going to grasp.

Soft robotics is an alternative to manipulate soft or delicate objects. It encompasses the field of robotics that uses soft materials or the ones that are interacting with soft or unknown objects [13–15] [16–18]. Even if the soft grippers seem to work well under uncontrolled events, they lack grasping force and precision [19], so some big and heavy objects or those that need precision grasps are hard to grasp or cannot be grasped with soft grippers.

To perform an adaptable and enveloping grasp in rigid or hybrid grippers an underactuated mechanism is mostly used [20–24]. Underactuation describes mechanical systems that cannot be commanded to follow arbitrary trajectories in configuration space. This condition can occur when the system has a lower number of actuators than degrees of freedom. In this case, the system is said to be trivially underactuated. There are diverse methods of manufacturing an underactuated gripper. Per example, using soft joints and a tendon-driven actuation, or a 4-bar linkage mechanism. The mechanism allows underactuation throughout passive adaptation.

4-bar linkages with parallel measures have emerged as a promising solution due to their ability to provide parallel movement of jaws, thereby ensuring reliable and effective grasping [25–27]. The parallel closing movement facilitated by 4-bar linkages with parallel measures contributes to a more reliable fixation of clamped objects. This is particularly beneficial when dealing with delicate or irregularly shaped objects that require a stable grip. The implementation of parallel four-bar linkages in gripper design enables more uniform force distribution on the clamped object. The parallel closing movement ensures that the gripping force is evenly distributed along the jaws, minimising the concentration of force at specific points. This uniform force distribution reduces the risk of localised stress or deformation on the object, further enhancing its stability during manipulation.

Robotic manipulation in human-oriented environments, such as agriculture, which is mostly a human controlled field, is expected to grow up continuously, since researchers seek to create robots that actively help in the daily lives of people [28]. When robotic manipulators are exploited in harvesting or crop removal, most of the times the task execution falls in the field of soft robotics [29].

Robots are useful in many tasks related to agriculture, such as soil preparation, seeding, transplanting, grafting, precision fertirrigation, pruning, deleafing, plague recognition, harvesting, pulverisation, crop removal, and post-harvesting tasks.

Grippers for grasping fruits and vegetables have been researched during the last decades [30–32]. Nowadays, robotics is exploited in many fields in order to help or even substitute human workers with the purpose of increasing the efficiency and speed of the work, but also to prevent people from risking their lives.

Several grippers have been specifically designed for manipulating various fruits and vegetables. For instance, grippers tailored for cucumbers [33], strawberries [34,35], tomatoes [36,37], peppers [38], oranges [39], radicchio [40], cherries [41], eggplants [34], kiwis [42], apples [43], soft foods [44], and multi-purpose grippers [45,46] have been documented in the literature. By tailoring the gripper design to the specific object, these studies aimed to optimise the grasping performance and enhance the overall efficiency of fruit and vegetable manipulation.

3. Methodology

3.1. Design specifications

The review of others grippers developed teach some lessons to be considered during the design of a gripper. From the initial one fully based on the Universal Gripper [47], to the previous gripper, with underactuation and a finger phalanx structure [10].

The grippers discussed in Section 2 have primarily been designed to cater to specific products, limiting their versatility. While some of these grippers can be adapted to handle other types of fruits, they often struggle to maintain stable grasps. On the other hand, grippers designed for general-purpose applications suffer from limitations such as excessive volume, low payload capacity, and lack of sensing capabilities.

To address the shortcomings of the literature grippers, this paper establishes a set of specifications that will serve as a guide for the development of a gripper specifically tailored for fruit and vegetable handling.

The specifications selected are the following:

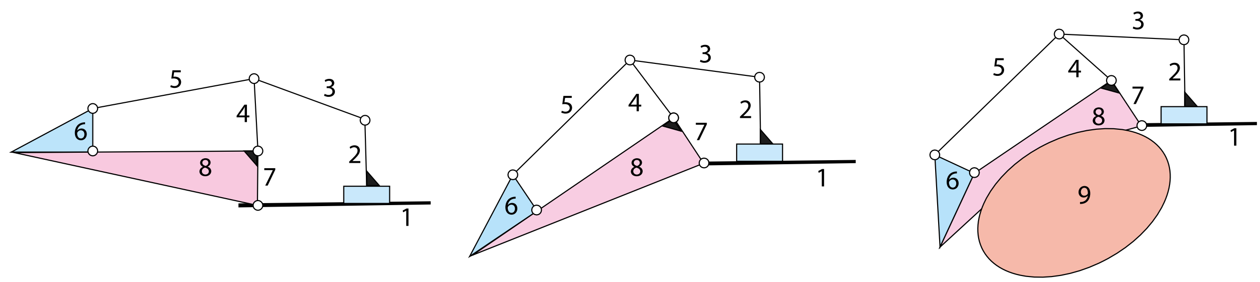


Fig. 2. Finger adaptation movement.

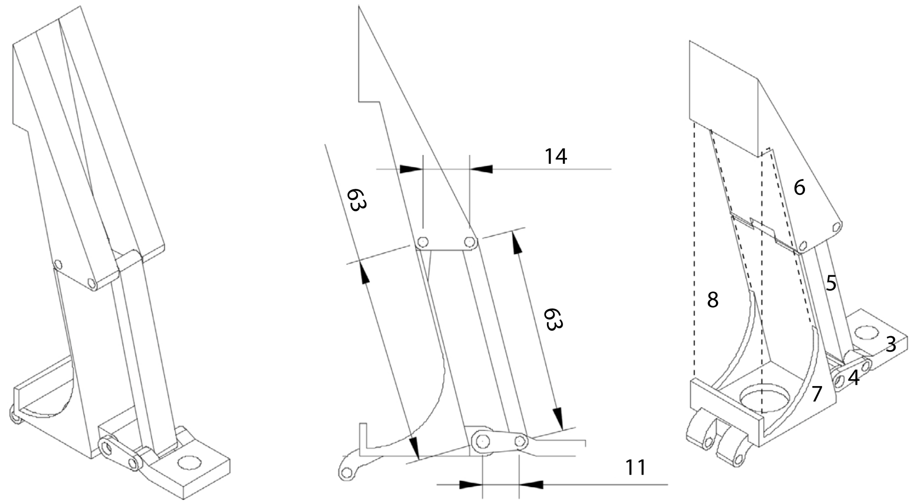


Fig. 3. Schemes and views of the finger structure. Measures in mm. Parts numbered.

- **Low grasping pressure on the rigid parts of the gripper contacting the object**. The gripper is intended to grasp soft and delicate objects that can be easily damaged, but the rigid parts of the gripper can cause deformations or damage to the grasped objects due to the lack of adaptability.
- **High grasping force**. The soft parts of the gripper will envelope the objects and distribute the grasping force around them. As in the previous specification, the finger mechanism must be designed so the actuation force transmits a higher grasping force to the soft parts than to the rigid parts.
- **High resistance to disturbances**. The gripper must be able to grasp a wide range of objects, it must be able to withstand external forces. In other words, it is necessary for the object to remain caged by the gripper. To achieve this, the soft or contacting parts must be made from a material with considerable roughness and the connection with the rigid parts must be sufficient to avoid detachment.
- **Small size**. The gripper's overall volume and parts should be reduced as much as possible. One of the desired characteristics of the gripper is the reduction of its weight and complexity. If the gripper is light, more robotic arms can lift it without losing as much payload. And faster movements come with less inertial loads.

3.2. Gripper design

The gripper consists mainly of four distinguishable parts.

- Fingers. This part performs the grasping action, enveloping and securing the objects. The finger itself also includes two different parts: a rigid and a soft one.
  - Mechanism. This part of the finger provides the main movement to the finger and transforms the actuation force into grasping force. This is done via rigid parts that combine into a mechanism.
  - Soft part. This part is used to dump the grasping force between the object grasped and the actuation system and to provide additional grasping surface.
- Base. This part is responsible for holding the fingers in a structure and joining them to a robot's arm or the system used to secure the gripper. It is made of a rigid material in order to provide a better union between the parts.
- Actuation: This part provides the gripper with the force to perform the grasping action.
- Perception. Several inexpensive sensors are embedded in the gripper to provide some reactiveness during the grasping process.

The fingers of the gripper are designed with an underactuated main structure. This design allows the gripper to function as a monolithic structure until the soft pad comes into contact with the object. At that point, only the distal part of the finger can move, enabling an enveloping grasp. When all three fingers work in unison, they can also provide an enveloping grasp. The grasping process is depicted in Fig. 2.

To address the challenge posed by the multi-degree-of-freedom nature of the finger mechanism, the soft part acts as a supportive element between the rigid structures. It secures the moving parts, allowing them to move only when external force is applied.

Fig. 3 illustrates the overall design and dimensions of the rigid part of the gripper.

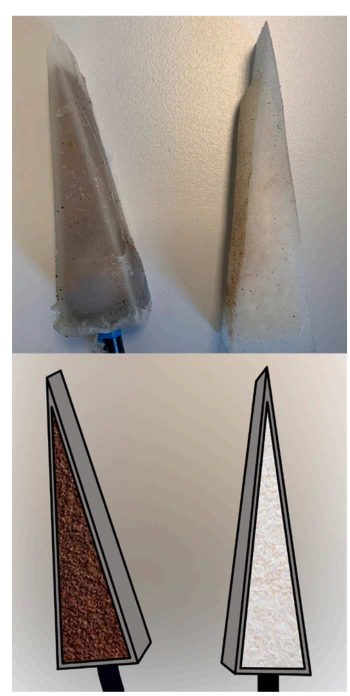
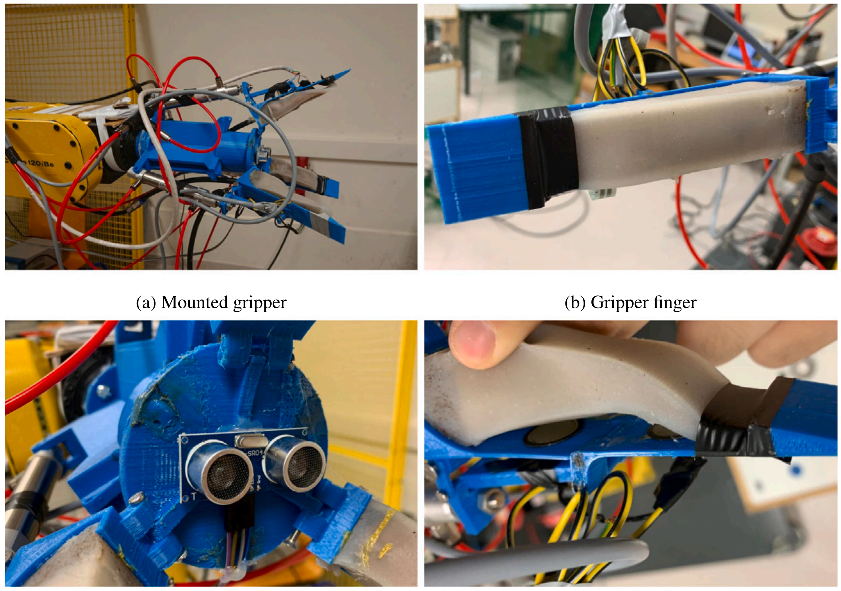


Fig. 4. Soft parts with coffee (left) and rice (right).



(a) Mounted gripper (b) Gripper finger

(c) Ultrasound sensor (d) Force sensors

Fig. 5. Gripper parts.

By combining the functionality of the various gripper components and employing the underactuated finger mechanism with the soft part, our gripper design offers versatility and adaptability in achieving successful grasping tasks.

A variable-stiffness silicone soft core is used for the fingers' soft parts. It uses the jamming principle for stiffness tuning, similarly to the Universal Gripper [3]. The inner cavity consists of an external layer of silicone filled with ground coffee and a tube with a filter, the filter is needed to prevent the granular material from being sucked out by the vacuum source.

In a normal state the silicone component is soft and adapts to the surfaces of the contacting products. When negative pressure is applied into the silicone core, it produces a vacuum that makes it to transition from a soft to a rigid state. When changing the amount of negative pressure in the cavity it allows to control the degree of overall stiffness in the finger.

In Fig. 4 two different soft parts are presented. Filled with coffee and rice. The figure also shows a cross-section to know how the materials are embedded into the soft part of the finger In the designed model coffee is used, due to the ease of manufacturing.

The soft core is embedded and glued in a cavity designed to prevent slippage, which is shown in Fig. 3, the cavity is the inner part of the falanxes of the finger, where the hole for the vacuum tubes can be seen. The core is inserted in the finger, as seen in Fig. 5(b).

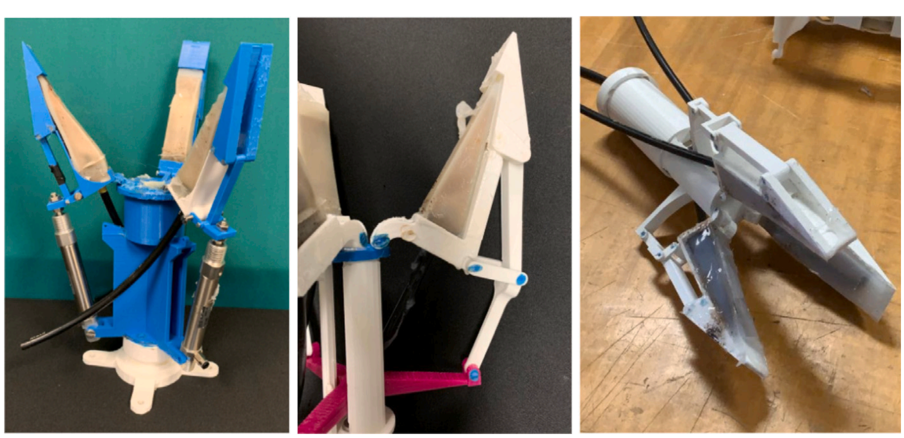
The creation of this soft core follows three steps:

- Construction with a 3D printer of an empty finger with a cavity for ground material, opened by the base.
- Filling of the cavity with grounded material, the tube and the filter are passed through the hole in the base.
- Closing of the base of the finger with additional silicone to seal the finger inside.

The fingers are actuated by pneumatic piston which produces the full open/closing of the fingers.

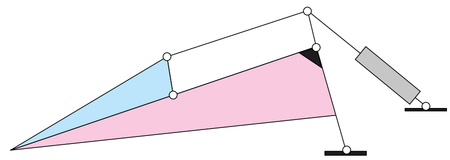
In addition to the main structure and the actuation system, the fingers are endowed with several types of sensors.

First, two cheap force-resistive sensors have been embedded between the finger's soft and hard parts. They allow to easily measure the contact force between the fingers and the products. Force-resistive sensors attached in the finger are shown in Fig. 5(d).

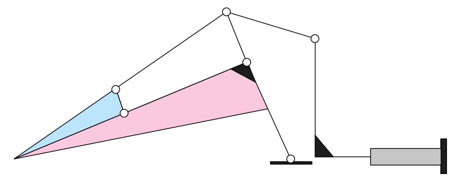


(a) VSGripV0 (b) VSGripV1 (c) VSGripV2

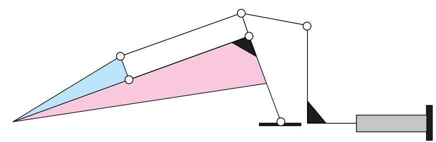
Fig. 6. Grippers.



(a) VSGripV0



(b) VSGripV1



(c) VSGripV2

Fig. 7. Sketch of the finger mechanism in each version.

Likewise, an ultrasound sensor has been added to the palm of the gripper to analyse the distance between object and gripper. It is used to establish an automatised process that does not depend on the object, but rather, on the distance between the object and the gripper. The ultrasound sensor is shown in Fig. 5(c).

The components allow the gripper to increase the variety of fruits and vegetables grasped, using the same programming code. Thus, the gripper is more flexible and capable. The overall design consists of the base holding threes fingers for a point-centred grasp. The grasping action is performed by three different pneumatic pistons, one per finger.

With all of these described elements, the gripper is manufactured using 3D printed parts of PLA for rigid elements and platinum core silicone for soft parts. They are shaped and cured using molds that are also printed from PLA. All of the finger parts are built together and then attached to the base. Finally, it is coupled to the robot's arm using a 3d-printed adapting piece.

Experiments may be carried out with the gripper attached to the robot. The final gripper, attached to the robot's arm, is shown in Fig. 5(a).

3.3. Improved design

The first prototype of the gripper will be called VSGripV0. As a result of the experimental tests, that will be described in Section 4, an improvement of the design has been proposed an manufactured. These versions of the gripper are called VSGripV1 and VSGripV2, as seen in Fig. 6. The grippers are built with the same overall structure. The three versions have three fingers with a centred grasp. All models were made following a soft-hard hybrid approach.

For the improvement, a series of benchmarking tests are executed with the initial gripper. Once the results from the test have been obtained, a second version is manufactured. The experiments are repeated in the second version. Finally, a third version is created.

The final version surpasses its predecessors in the benchmarking tests. These experiments are explained in greater detail in Section 3.4.

The soft part of the fingers is similar for the three models. The soft core generates a change in its stiffness, using a principle similar to that of the Universal Gripper [3]. For the initial version, VSGripV0, and the first version, VSGripV1, the design of the soft part remained unchanged. In the final model, VSGripV2, due to low values found in the slipping tests, the design has been changed to ensure improvement. The soft part has been cured along the rigid mechanism parts, offering better resistance. This prevents the soft part from being detached from the linkage bars due to the grasping force.

The mechanism has been changed in the first version of the gripper to determine whether or not it improves the grasping results. The mechanism starts from a 4-bar linkage system which bars are parallel two-to-two. In the VSGripV1 it is changed into a non-parallel one. Both undergone the benchmarking tests to provide data for a correct improvement process.

However, due to a decrease in the goal desired values of the mechanism, which have been extracted from the optimisation benchmarking tests, for the VSGripV2 the transmission mechanism has been changed again.

Having made the VSGripV2 it with similar measures to those from the initial one, the parallel two-to-two mechanism. But changing them to be equal pairwise. Sketches of the mechanism with the actual proportions are shown in Fig. 7.

VSGripV0 is actuated using three pneumatic pistons, one per finger, at a pressure of 1.33 bar. To reduce gripper volume and components, in the upcoming versions, only one piston is used at 4 bar pressure with a mechanism that converts piston movement to the actuation movement of the gripper fingers. The increase in piston pressure is due to the force transmitted to each finger; therefore, the pressure is triplicated from 1.33 bar to 4 bar.

3.4. NIST benchmarking tests

To test the gripper capabilities and guide the improvements from the initial to the final version, four different benchmarking tests were used. These tests are adaptations of those proposed by the NIST protocols [4] to our custom test bench for artificial hand prototypes (PACMAR platform) [48,49]. All tests are repeated 20 times per gripper. In the following sections we show the proposed tests.

3.4.1. Grasping force

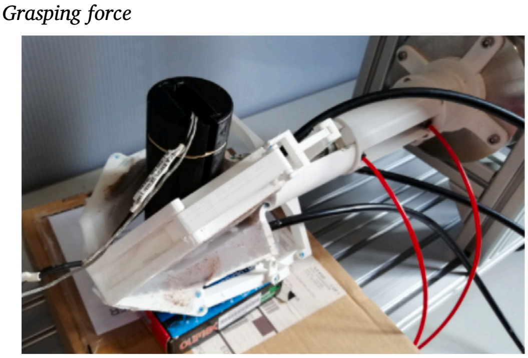
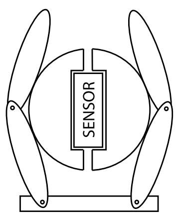


Fig. 8. Grasping Force.

The objective of the grasping force test is to measure the maximum grip force exerted by the gripper on a cylindrical object. Fig. 8 presents the improved gripper when performing this test.

The cylinder artefact is composed of two half cylinders having a diameter of 50.8 mm. The artefact has two load cells to measure the grasping force. They are used to measure the internal force transmission of a grasp. Two different split cylinder artefact orientations have been used, as it can be seen in Fig. 9:

- In the 0 degree orientation, the load cell axis is parallel with the palm surface.
- In the 90 degree orientation, the load cell axis is perpendicular to the palm surface.



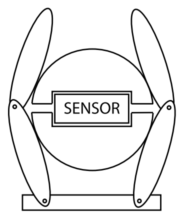


Fig. 9. Grasp Strength configuration. For 0° (left) and 90° (right).

Taking force measurements in two orthogonal directions provides the necessary measurements to approximate a resultant internal force since this artefact design only measures force in one direction.

The tests are performed fully closing and opening a wrap grasp around the artefact for both orientations under maximum allowable power. The sensor data is recorded throughout the test, and the resultant internal force is calculated.

3.4.2. Finger strength

The finger strength test measures the force at the tip of the finger. In our case, this is the force exerted by the rigid parts. Therefore, the results of this test should be as low as possible to prevent excessive damage to the grasped objects. The position of the VSGipV2 performing the test is shown in Fig. 10.

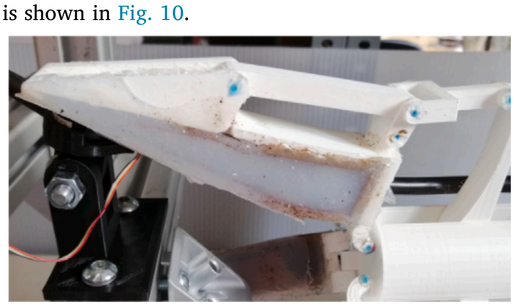


Fig. 10. Finger strength test.

One significant finger-object configuration for benchmarking occurs when the induced moment arm from making contact is at its maximum. For most gripper designs, this occurs when a finger is fully extended and all finger links are extended, as shown in Fig. 10. Some minor adjustments should be made to this finger-object configuration. The finger's contact force must be normal to the sensor contact surface. This prevents dispersing contact force.

Using the finger-object configuration described, the finger under test is positioned just above the force sensor and a zero force reading is verified. Under position control, the finger is then commanded to close completely which should induce control saturation.

The force sensor data is recorded throughout the test. The resultant value from the test is the one obtained at the control saturation.

3.4.3. Slip resistance

This test directly measures the maximum shear force that an object can withstand before slipping from the gripper during the grasping process. It also measures the maximum payload that the gripper can withstand. Fig. 11 shows VSGripV2 performing the test.

Slip resistance is a kinetic measure of a robotic gripper's ability to resist slipping during a force disturbance. The main objective of this test is to investigate the surface friction properties of the hand and possible payload [4].

To perform the test, a PVC pipe of 75 mm diameter is placed in the robotic hand. Using a wrap grasp at maximum power with the highest possible number of hand-object points of contact the pipe is grasped.

At a controlled rate of increasing force the pipe is pulled with a linear actuator, recording force until gross slippage is visually confirmed between the gripper and the pipe.

3.4.4. Cycle time

Grasp cycle time is a measure of the minimum time required for a robotic hand to achieve full closure from a known pre-grasp configuration and to return to its pre-grasp configuration from the grasp position. This measure provides information on a specific hand's closing/opening speed capabilities [4].

The tests allow to know the time spent for the grasping action. Even if this does not measure a mechanical property of the gripper it does measure a capability in order to perform pick and place tasks in less time.

To perform the test, the artefact described in the grasping force test is placed in the gripper opened palm. The cycle of a wrap grasp is executed, opening and closing as fast as the gripper can. The grasp cycle time is obtained thought the time measured between the force peaks read from the sensors. The force peaks are generated at the contact instant while carrying out the grasping cycles.

3.5. Edibles grasping test

To test the effectiveness of the gripper on fruit and vegetable grasping, an additional experiment has been performed. Past experiments with food have used mangoes to determine their ripeness [50].

Here, we propose a new experimental test to measure how the gripper works when grasping real-world objects. These objects are fruits and vegetables due to the fact that they are fragile and deformable and must not show any signs of damage after their manipulation.

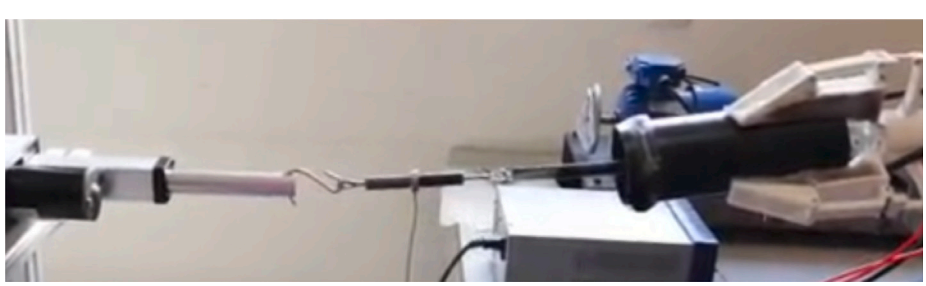
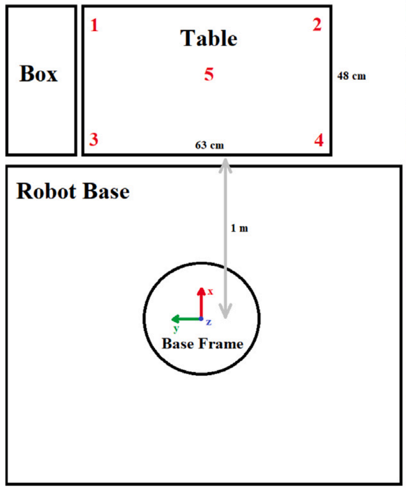
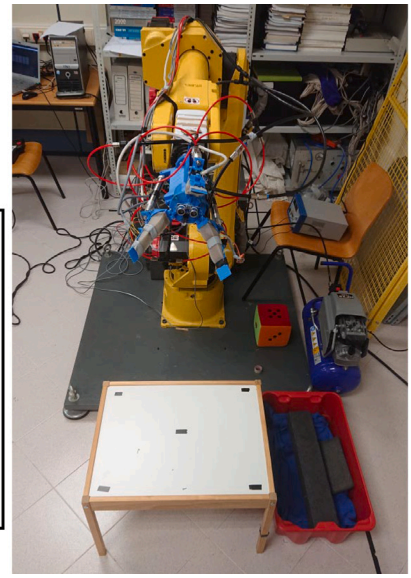


Fig. 11. Test with the VSGripV2 gripper.



(a) Experimental setup scheme



(b) Real-life experimental setup

Fig. 12. Experimental setup.

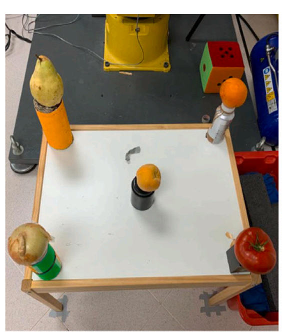
The test consists of grasping ten different fruits and vegetables from a table, in sets of five, and transporting them to a box set next to the table. All of this must be achieved without the fruit or vegetable falling or the grasp failing. Objects will be set at different heights to test the ultrasound sensor at distinct depths.

The experimental setup consists of a Motoman Robot Arm with the gripper attached to it, a table for grasping the items and a box where they are subsequently deposited. They are placed at distances as seen in Fig. 12(a). In Fig. 12(b), the position of the fruits and vegetables to be used for the experiments is shown in the real table, marked with black tape.

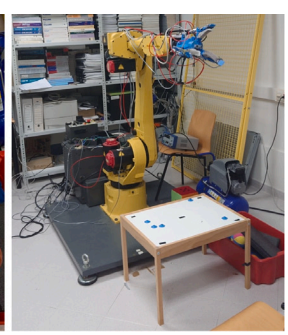
3.5.1. *Experimental steps*

The following steps are used for the test. Steps three to eight are repeated for each fruit and vegetable on the table. Visual representations of some of the steps are shown in Fig. 13:

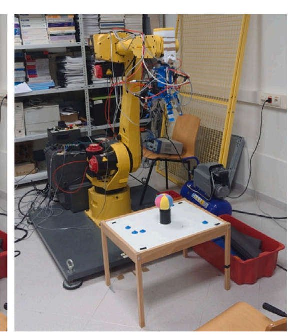
1. Object placing: Items are allocated in the five marks established in the previous image. For a better grasp, they may be placed over a stand to avoid rolling over the table. This step is shown in Fig. 13(a).



(a) Object collocation

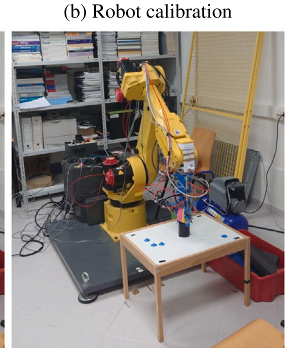


(b) Robot calibration

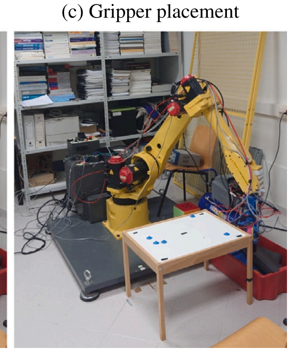


(c) Gripper placement

(d) Gripper approach



(e) Object grasping



(f) Item placement

Fig. 13. Testing steps.

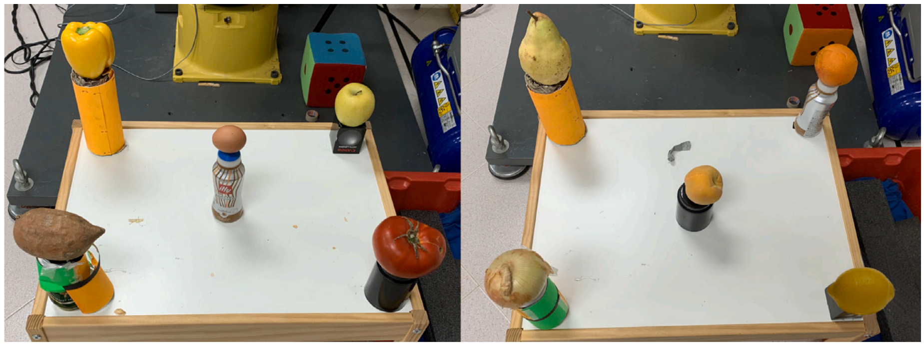


Fig. 14. Objects used in the test.

2. Robot calibration: The robotic arm goes to the zero position to calibrate all of the motor encoders. This step is shown in Fig. 13(b).
3. Gripper placement: The gripper is placed over the object with the fingers pointing downwards. This step is shown in Fig. 13(c).
4. Gripper approaching: The gripper begins a vertical approach to the object until the ultrasound sensor reads a distance of 70 mm and then stops. This step is shown in Fig. 13(d).
5. Object grasping and force measure: The gripper is closed and force sensors of the fingers begin to read the grasping force values.
6. Void application.
7. Item placement: The robot arm rises vertically, then reaches over the box and finally, performs a vertical approach inside the box. This step is shown in Fig. 13(f).
8. Object release: The gripper is opened and the item is released into the box.
9. Reset: The arm returns to a zero position.

The edible grasping test is repeated 10 times per fruit or vegetable.

The fruits and vegetables are shown in Fig. 14. They are: a pepper, an apple, an egg, a sweet potato, a tomato, a pear, an orange, a peach, an onion and a lemon. The objects will be grasped in two different groups, also presented in Fig. 14. The first set contains the pepper, apple, egg, sweet potato and tomato, and the second set includes the pear, orange, peach, onion and lemon.

The fruits and vegetables grasped are placed in objects of different heights to lift them. This is done to test the ultrasound sensor. The sensor provides a distance feedback for the closed-loop approaching control.

The object disposition will avoid that edibles with diverse height or possible different positions do not interfere with grasping control. This eliminates the need to change the code for fruits and vegetables.

The test can also measure if the objects are damaged while grasping or not. This is done by empirically analysing the grasped fruit after the manipulation process. For each fruit involved in the test it must be annotated if it result in a damage while grasping or not.

4. Results

The benchmarks tests explained in the above section are used to measure the alternative designs of the gripper. Actually, these tests are used to evolve these designs from the others. The next sections detail the results obtained.

4.1. NIST benchmarking tests results

Tables 1 to 4 show the results obtained in each test for the different gripper versions, including the effect of applying a void in the soft part for VSGripV2, exposed as VSGripV2-void.

For the sake of comparison, these tables also include the results for tow commercial collaborative grippers: the Robotiq 3 fingered Hand and the Barrett Hand [51]. The results of these two grippers have not been obtained experimentally on this work but has been extracted from Falco et al. [4].

The results for the cycle time test are not available for the Barret and Robotiq Hand. Also, since the cycle time is mostly a natural characteristic, it also includes the results for a human hand [49].

Table 1 shows grasp strength test results. VSGripV1 performed worse than VSGripV0. Therefore, VSGripV2 had a mechanism similar to VSGripV0, with some changes in dimensions. This resulted in an improved grasping force. The application of void allowed additional improvement in grasp strength.

As all the tests are repeated 20 times, in the corresponding tables the mean values and the superior and inferior values of the 95% confidence interval are written.

Table 1
Grasp strength results.

Version	Mean force	95% Inf.	95% Sup.
VSGripV0	16.94 N	16.35 N	17.53 N
VSGripV1	6.79 N	6.40 N	7.18 N
VSGripV2	20.91 N	19.76 N	22.05 N
VSGripV2-void	23.33 N	23.08 N	23.59 N
Robotiq	47.02 N	44.37 N	49.47 N
Barrett Hand	118.98 N	101.26 N	137.85 N

Table 2 shows the results for the finger strength test. The changes made from VSGripV0 to VSGripV1 changed the finger force in the opposite direction to that desired for grasp strength.

Table 2
Finger strength results.

Version	Mean force	95% Inf.	95% Sup.
VSGripV0	7.50 N	7.40 N	7.60 N
VSGripV1	16.91 N	16.76 N	17.06 N
VSGripV2	7.27 N	7.19 N	7.34 N
VSGripV2-void	7.66 N	7.63 N	7.68 N
Robotiq	8.24 N	8.00 N	8.80 N
Barrett Hand	30.44 N	29.39 N	30.95 N

As seen, the VSGripV2 of the finger force returns to its original values. When activating the vacuum, the change of the finger force of VSGripV2 remains somewhat stable, with only a minor increase.

The third test is the slip resistance test, shown in Table 3. The table shows how, in each version, the slip resistance continues to improve by making certain changes. In the first version, the rigid distal part of the finger is covered with silicone to provide extra friction thanks to the material's roughness. In the final model, the characteristic is improved by fusing the soft parts into the rigid structure, directly curing the silicone core on it. This gives the finger an improved stability of parts. When the void is activated, slip resistance increases considerably, demonstrating a relationship.

Table 3
Slip resistance results.

Version	Mean force	95% Inf.	95% Sup.
VSGripV0	25.13 N	22.57 N	27.69 N
VSGripV1	36.50 N	33.98 N	39.02 N
VSGripV2	59.26 N	53.63 N	64.88 N
VSGripV2-void	71.85 N	68.70 N	75.01 N
Robotiq	84.64 N	82.00 N	86.00 N
Barrett Hand	164.73 N	145.00 N	166.00 N

The final test is the cycle time test, presented in Table 4. This test shows the speed of object grasping and releasing. It is not especially important in the design of the gripper, but it does acquire relevance in terms of gripper applications.

Table 4
Cycle time results.

Version	Mean time	95% Inf.	95% Sup.
VSGripV0	1.23 s	1.13 s	1.34 s
VSGripV1	1.36 s	0.55 s	2.18 s
VSGripV2	0.35 s	0.29 s	0.40 s
VSGripV2-void	0.44 s	0.41 s	0.47 s
Human Hand	1.32 s	1.28 s	1.35 s

4.2. Edible grasping tests results

In environments such as the pick and place of production lines, speed is important in order to perform the task as quickly as possible, since time is money in this industry, with less cycle time more operations can be done. This parameter is better as it gets more reduced.

For the last model, cycle time is reduced by less than half of that of the first model, upgrading the gripper performance in speed tasks. Making it faster to provide pick and place operations.

4.2.1. VSGripV0

Table 5 shows the results of the grasping edible test applied on VSGripV0 The second column shows the number of damaged fruits and vegetables after 10 trials. The third column of Table 5 shows the average grasping force each object in Newton.

The gripper has a perfect ratio of 100% success for grasping all of the objects. None of the edibles was released involuntarily from the gripper grasp during the tests.

Table 5
Results for VSGripV0.

Object	Damaged	Grasp force
Pepper	5/10	3.12 N
Apple	7/10	9.77 N
Egg	0/10	15.40 N
Sweet Potato	2/10	4.16 N
Tomato	7/10	14.04 N
Pear	9/10	6.27 N
Orange	1/10	5.86 N
Peach	3/10	0.83 N
Onion	0/10	5.43 N
Lemon	0/10	3.20 N

4.2.2. VSGripv2

VSGripV2 is an improvement of VSGripV0. It is once again tested for the fruit and vegetable grasping task. In this test instead of the whole test a reduced version is performed. Due to the fact that the only desirable measure is the damage exerted to the edibles.

The gripper is tested with the objects used in the previous test (pepper, apple, egg, sweet potato, pear, orange, peach, onion and lemon). Extra objects are added to test its adaptability. The manipulator is shown in 15.

The gripper results are shown in the Table 6. As it was said beforehand, as the grasping force is not the point on this test only the damaging results are shown.

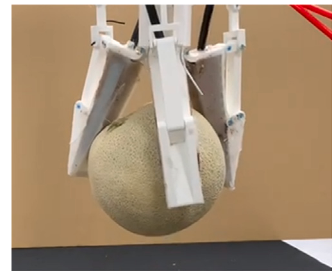


Fig. 15. Gripper used in the test.

Table 6
Results for VSGripV2.

Object	Damaged
Pepper	0/10
Apple	0/10
Egg	0/10
Sweet Potato	0/10
Tomato	0/10
Pear	0/10
Orange	0/10
Peach	0/10
Onion	0/10
Lemon	0/10

5. Discussion

5.1. NIST benchmarking tests

We conducted experiments to evaluate the grasping performance of VSGripV1 and VSGripV0. The results clearly indicated that VSGripV0 outperformed VSGripV1 in terms of grasping force. This observation prompted us to further improve the design and introduce VSGripV2, which incorporated modifications in dimensions and additional enhancements.

To gain insights into the reasons behind the superior performance of the parallel two-to-two 4-bar linkage system (VSGripV0 and VSGripV2), we investigated the mechanical principles at play. The parallel configuration of the linkage system allows for a more efficient transfer of forces and moments during the grasping process. By distributing the applied forces evenly across the fingers, the parallel system minimises the occurrence of unwanted bending or twisting moments that could compromise the grasping force.

This set of benchmarks has been used to test the initial design of the gripper, VSGripV0, and from the results modifications of the design, VSGripV1, and VSGripV2, has been proposed and tested again. These results showed that the final version, VSGripV2 offer a increment in the performance in all four test:

- Grasping force: 23.54% VSGripV2 and 37.72% with void
- Finger force: 3.16% VSGripV2 and −2.08% with void
- Slip Resistance: 137.31% VSGripV2 and 185.91% with void
- Cycle Time: 71.54% VSGripV2 and 64.22% with void

Furthermore, the number of pieces and actuators have been reduced in VSGripV2 has been reduced, achieving improved results for the objective of being simpler and lighter.

With respect the comparison with the commercial collaborative grippers, they achieve better results than our prototypes. So, there is still better improvements to be done to the gripper. However, the VSGripV2 shows faster cycle times than the human hand.

(a) Persimmon (b) Tomato (c) Apple

Fig. 16. Damage seen in fruits.

5.2. Edible grasping tests

From the results in the tables in Section 4, it is possible to extract several conclusions. Firstly, it is found that the change in stiffness can be made automatically, thanks to the force sensors. When the force exceeds a specific value, 5 N per example, the object may be too heavy to be grasped by the soft form of the gripper, or it may be too hard to be grasped by a soft gripper. If this is the case, the gripper can adapt by instantly changing its stiffness. This would increase the range of graspable fruits and vegetables. Secondly, the success rate in grasping the objects validates the design approach since the gripper is able to successfully grasp the wide diversity of shapes and mechanical properties of the fruits and vegetables.

Finally, the gripper can also change its grasping force in a passive manner, depending on the object grasped. Therefore, it can be used to grasp different objects.

Objects having a more similar distribution are lemons, peaches, sweet potatoes and peppers. The passive force adaptation provided by the materials and the design elections allows the gripper to grasp different kinds of objects. The grasping is carried out without the need for external components or position feedbacks that over-complicate the control.

Once all the edible grasping tests have been performed, the grasped fruits are analysed to determine if they have been damaged. Some examples are shown in Fig. 16. The fruits and vegetables grasped with the improved gripper are unharmed. In contrast, some of the edibles grasped with the robotic gripper reveal marks and scratches, suggesting that the improved gripper can grasp fruits and vegetables without harming them.

6. Conclusions

In this paper, a variable-stiffness gripper has been designed, improved and tested. Several design iterations have resulted in an improved variable-stiffness gripper. The final gripper design is able to grasp diverse fruits and vegetables without damage.

This gripper overcomes some of the problems set up in fruit and vegetable picking systems. It has a simple design, with sufficient payload to grasp all of the expected objects and with an adaptability to grasp several fruits and vegetables. Based on the experimental results, it is evident that the gripper can grasp a wide range of items.

A subset of the NIST benchmark set has been used to evaluate the mechanical properties of the gripper prototypes. Importantly, a new benchmark test, the edible grasping test, has been designed to be used on this specific scenario.

These tests are of great importance to help the design process itself. Soft materials are difficult to model mathematically, and real-world experiments are necessary to measure their performance.

In future studies, additional grippers will be tested using this protocol and may be extrapolated to the research of anthropomorphic hands or prostheses. This will potentially expand the range of all possible tests. More elaborate versions of these fingers could be used to implement variable-stiffness for multi-finger hand-like grippers such as the Barrett Hand [51] or the Schunk Hand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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