Alexandria Engineering Journal (2021) xxx, xxx–xxx

HOSTED BY
ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

Design and analysis of a variable-stiffness robotic gripper

Daniel Cardin-Catalan [a,*], Simon Ceppetelli [b], Angel P. del Pobil [a,c], Antonio Morales [a]

[a] Robotic Intelligence Laboratory, Department of Computer Science and Engineering, Jaume I University, Av. de Vicent Sos Baynat, 12071 Castellón de la Plana, Spain
[b] SIGMA Clermont, Campus des Cézeaux, 63178 AUBIERE CEDEX, France
[c] Department of Interaction Science, Sungkyunkwan University, Seoul 110-745, South Korea

Received 29 July 2020; revised 29 January 2021; accepted 17 June 2021

KEYWORDS

Robotics;
Variable-stiffness;
Gripper;
Grasping;
Benchmarking

Abstract This paper presents the design and analysis of a novel variable-stiffness robotic gripper, the RobInLab VS gripper. The purpose is to have a gripper that is strong and reliable as rigid grippers but adaptable as soft grippers. This is achieved by designing modular fingers that combine a jamming material core with an external structure, made with rigid and flexible materials. This allows the finger to softly adapt to object shapes when the capsule is not active, but becomes rigid when air suction is applied. A three-finger gripper prototype was built using this approach. Its validity and performance are evaluated using five experimental benchmark tests implemented exclusively to measure variable-stiffness grippers. To complete the analysis, our gripper is compared with an alternative gripper built by following a relevant state-of-the-art design. Our results suggest that our solution significantly outperforms previous approaches using similar variable stiffness designs, with a significantly higher grasping force, combining a good shape adaptability with a simpler and more robust design.

1. Introduction

Grippers composed of rigid parts have been a dominant solution for robotic manipulation throughout the years. Rigidness, mostly of fingers and pincers, allows the use of grippers in typical industrial applications to perform repetitive tasks with precision. They are still a primary solution in many fields [1]. However, their lack of adaptation to contacts in applications where softness and flexibility are required make them an unsuitable solution. More recent approaches have opted to apply principles of soft robotics to design more flexible grippers. Soft robotics encompasses the section of robotics built with soft materials or the ones that are interacting with soft or unknown objects [2–5]. Rigid and soft grippers have their pros and cons. Rigid grippers were originally designed for industrial applications in which the task specifications requires high precision and the ability to exert large forces, but at the

* Corresponding author.
E-mail address: cardin@uji.es (D. Cardin-Catalan).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2021.06.045
1110-0168

cost of a low mechanical flexibility which was counterbalanced with adaptive control methods. In non-traditional scenarios in which unexpected and uncontrolled events may arise, soft grippers show a level of robustness, adaptability and compliance that rigid grippers cannot provide, this time at the cost of lower precision and grasping force [6].

This paper describes the design of the RobInLab VS gripper that offers the properties of both approaches. It has the ability to adopt rigid configurations in some moments, when holding and transporting objects, and also it can exhibit soft properties on other occasions, specially when adapting to soft and fragile objects. The proposed solution uses a variable-stiffness soft silicone core that can change its own stiffness at will and perform as both, rigid and soft. It is constructed with granular material contained on an external layer of silicone. This approach follows the principles described for the first time for a gripper based on the jamming of granular material [7]. It uses an air-compressor and a vacuum pump to provide a negative air pressure which creates a hard-like state in the core. To configure the shape of the fingers and allow to control their movement, a combination of rigid and soft parts are made to create an external skeleton, which is wrapped around the variable-stiffness silicone core.

The solution proposed in this paper builds on the approach followed by Mizushima et al. [8]. A second goal of our research is to evaluate our new design by comparing both of them. With that purpose, a prototype replica of that gripper, the Mizushima VS gripper, was constructed and both designs were compared using five experimental tests specifically designed to benchmark variable-stiffness grippers.

The contribution of the paper is double. On the one hand, we propose a novel design for a variable-stiffness gripper, which is experimentally evaluated and compared with and alternative design. Our experimental results suggest that the new RobInLab VS gripper performs at a much higher level in the benchmark tests, with a significantly higher grasping force, combining a good shape adaptability with a simpler and more robust design. On the other hand, the set of five experimental benchmarking tests that we designed and implemented to evaluate the gripper prototypes is a contribution in itself that fills a lack of benchmarks specifically focused on variable-stiffness grippers.

The paper is organized as follows. Section 2 reviews the existing different procedures to create variable-stiffness grippers along with some models which have special interest for our research. Section 3 describes the design and construction of the RobInLab VS gripper and the Mizushima VS gripper. The bechmarking tests are described in Section 4. Finally, the experimental results are summarized and discussed in Section 5. The conclusion of the work is presented in Section 6.

2. State of the art

Recent approaches [8–17], investigate grippers with stiffness that can be modified in a controlled way. This gives these grippers more grasping capabilities by allowing them to deploy different grasping forces depending on the object that they are going to grasp, typically offering a controllable duality for working in a rigid or soft manner.

Variable-stiffness grippers have different methods to change their own stiffness. In the last few years different approaches have been developed to induce a variation in the mechanical properties of the grippers. Some of them apply materials whose stiffness varies according to their temperature [9,10,12,16] (see Fig. 1a). Other grippers, use magnets or springs as external elements to change their grasping force [11,17] (Fig. 1b) or the gripper overall stiffness. Others, such as the universal gripper [7] or derivatives [8], work thanks to the interference of granular material inside a sealed plastic cover when negative air-pressure is applied (Fig. 1c). Last, there are grippers which use co-actuation as a way of tuning their stiffness [14] (Fig. 1d).

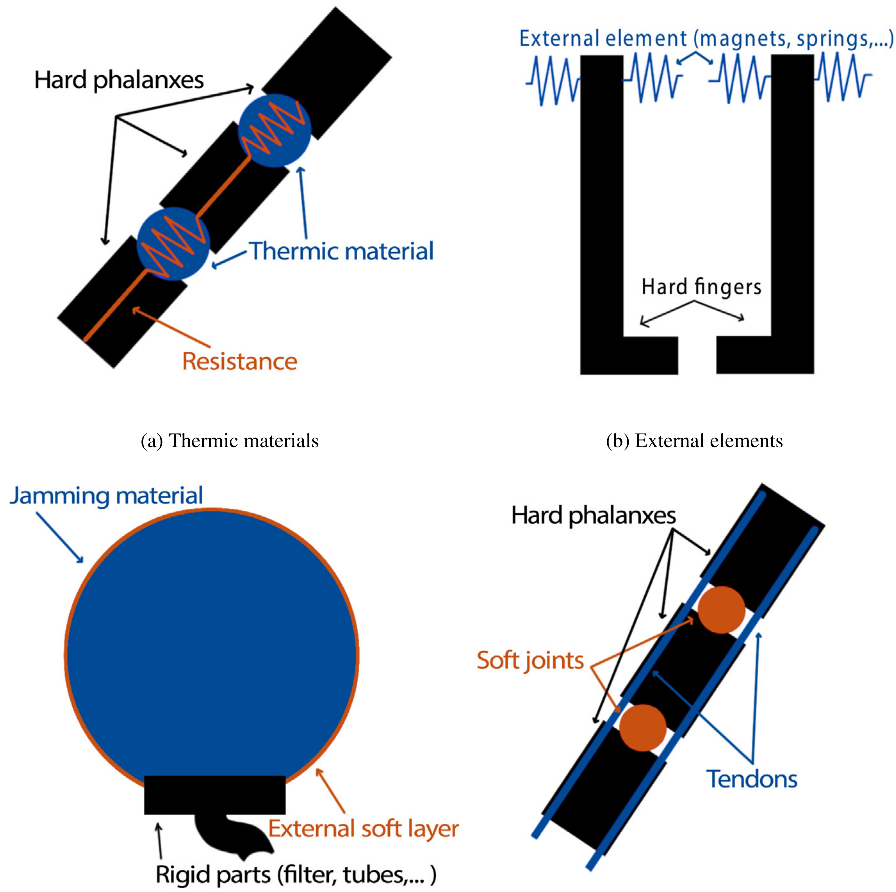
Each of the above methods shows some weaknesses and strengths. Thermal materials require some time to change between stiffness states. This delay often makes this principle unsuitable to be applied on manipulation or grasping tasks which require faster actuation. The second approach uses external elements to create the difference of stiffness or impedance, these elements add extra volume to the gripper which turns out heavier and bulkier, that can be a nuisance in tasks were the objects are close and only one has to be grasped without altering the others.

The Universal Gripper, however its adaptability, can only grasp objects smaller than its own surface or with irregularities around which it can adapt its shape, not being able to grasp large or smooth objects. Finally, the co-actuation approach generates an excessive inner stress in the finger structure, causing undesirable deformations while grasping.

Lastly, there is an alternative manner to change the grasping force of the gripper by controlling the impedance through the actuation system. It is not a change in the stiffness of the gripper itself to alter the grasping force, but rather this is changed as a result of controlling the power in the actuation. This property is also known as *variable impedance* [18–21] (see also [22] for a review on variable impedance actuators). Not only has variable impedance been applied for interactions with unknown and dynamic environments, but also for human-robot interaction [23].

The approach proposed in this paper aims at being able to change the stiffness almost instantly, trying to keep a simple design without the addition of extra elements in order to change its own stiffness, having the capability to grasp as many objects as possible, and all of this without generating inner stress that would produce undesirable effects on the grasping action.

A mechanical principle which specially attracted our attention for design purposes was the one used for the universal gripper. The universal gripper [7] works thanks to the interference of granular material inside a sealed plastic cover. When negative pressure is applied into the plastic cavity with the granular material inside, thanks to the friction among the inner material particles, the shape of the cavity is maintained as a rigid-like object. Consequently, if the cover has been previously adapted to the object's shape, when negative pressure is applied it will hold the object and perform a firm grasp. Since its first appearance, several researchers have made some improvements on it such as: changing the inner fluid to improve its performance [24]; making it work with positive pressure instead of vacuum [7]; using it for grasp computation [25]; and even making arrays of little sticks manufactured like the universal gripper to perform grasps [26], with these improvements it can even be used in diverse environments such as underwater operations [27].



(a) Thermic materials (b) External elements

(c) Jamming principle (d) Co-actuation

Fig. 1 Schemes of stiffness tuning methods.

An interesting work that tries to combine the jamming principle with a rigid skeleton is that of Mizushima et al. [8]. They design and construct a four-fingered gripper where each finger is composed by an inner articulated skeleton with rigid links actuated by tendons. The fingers are completely covered by an outer capsule filled with granular material. This design allows to have and under-actuated system that conforms easily when the air pressure is off the jamming capsule, but gets stiffer when it is activated. The binary change of stiffness is achieved by activating/deactivating the negative pressure. See Section 3.2 and Fig. 4 below for more details about this gripper.

The design proposed for the RobInLab VS gripper builds on the Mizushima VS gripper. Thus, an additional goal of this paper is to compare both grippers to assess their performances. In order to do that, a three-fingered replica of the Mizushima VS gripper was constructed.

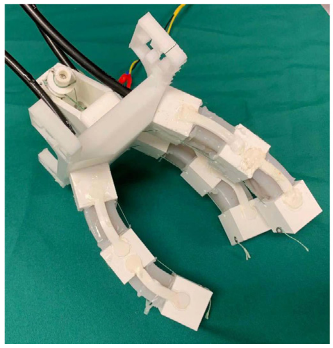
3. Methodology

3.1. RobInLab VS gripper

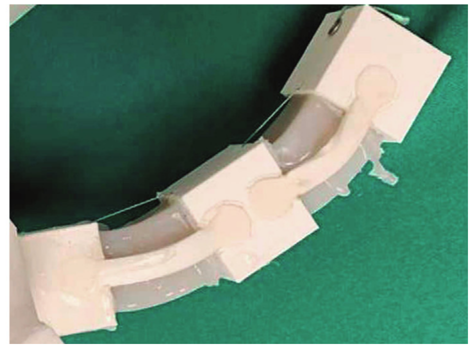
The gripper design, shown in Fig. 2a, is intended to overcome the problems explained in Section 2 of existing variable-stiffness grippers. These refer to the ability to change stiffness instantly, avoid using external elements to change the stiffness, be able to grasp a large variety of objects, and avoid large inner stress due to co-activation or similar methods.

Each finger is constructed with a core that uses the jamming principle for stiffness tuning (see. Fig. 3). It consists of an empty rectangular silicone shell filled with ground coffee. The shell provides the finger with the desired shape and acts as an envelope to prevent any leaks. When negative pressure is applied into the silicone shell, it produces a vacuum that makes the finger pass from a soft to a rigid state. The amount of negative pressure allows to control the degree of stiffness. This inner core is the main part of the finger, but it lacks a controlled and guided way to conform to a given posture. To guide conformation of the core's shape and provide it with strength and reliability, three phalanges of rigid plastic are added as a form of exoskeleton. The phalanges have a simple empty cubic design with a path to pass the tendons and the soft unions. The phalanges are linked together with soft joints, which also help with the movement and endow the finger with enough resilience to return to the resting position by itself. These soft joints are made of flexible 3D-printable material known as FilaFlex®. This structure allows to perform a sub-actuated grasp with the finger keeping the properties of the universal gripper.

As there is not any second tendon or mechanical actuation that opposes the main movement, because the stiffness change



(a) Complete gripper



(b) A single finger

Fig. 2 The RobInLab VS gripper.

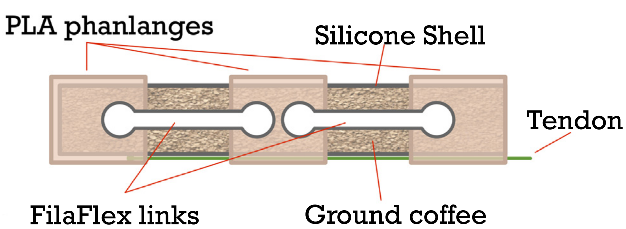


Fig. 3 Scheme of the finger.

is induced by pressured air, there is no extra inner stress in the finger, excluding the one created by the granular material.

The tendons pass through the rigid parts of the finger, i.e. the PLA phalanges (see Fig. 2b). This design decision was made in order to avoid the problems that the contact between the tendon and the silicone shell would cause. Namely, the increased force needed from the motor to move the finger, as well as the abrasion on the silicone shell caused by the tendon.

Finally, a support structure to hold the fingers was also designed and constructed. This structure accommodates three fingers in a 2 to 1 opposing formation. This configuration was chosen in order to simplify the gripper design while keeping its functionality. Three fingers provide more stability than two fingers while grasping, but adding more fingers would overcomplicate the design and would require more material. The pictures in Fig. 2 show a prototype of the complete gripper along with a detail of one finger.

For the gripper and, specifically, the finger design we have followed a bio-inspired approach, which has yielded good results in the field of robotics [28–30]. With bio-inspiration the finger design can be simplified; indeed, a clever morphological design inspired by natural systems provides the gripper with embodied intelligence [3,31] allowing us to eliminate extra elements that would have performed the same functions, which was one of our goals.

3.2. Mizushima VS gripper adaptation

In order to compare the RobInLab VS gripper with the Mizushima VS gripper, a prototype of the latter was built following the description in [8] (see Fig. 4). The original gripper and the finger structure are depicted in Fig. 4. Our prototype replica consists of three fingers (Fig. 5a) instead of the four originally described in [8]. The main reason is to make it comparable to RobInLab VS gripper.

The materials used to build the Mizushima VS gripper are the same as the ones used in the RobInLab VS gripper, for rigid and soft parts, PLA and platinum-core silicone respectively. However, the granular materials used to change the stiffness are different. We used rice for the Mizushima VS gripper to be more faithful to its original design description, instead of the ground coffee used for the RobInLab VS gripper.

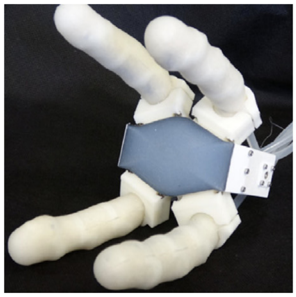
The fingers have been designed following the guidelines from the original model. The phalanges are made in such a way that the gripper movement resembles that of the human hand. On each joint a blocker is mounted so the granular material cannot roam freely inside the finger rigid structure. The pieces are 3D-printed and mounted all together. Fig. 5a and b show the resulting gripper as well as some inner details. The dimensions of all the parts followed the design description of the original paper.

The finger inner structure is embedded into a silicone shell and filled with rice as in the original model. The rice serves as the granular material to produce the jamming effect. To operate the finger one tendon is passed through the phalanges along a nylon tube to insulate it from the jamming material so that it can actuate the phalanges without interfering with the vacuum encapsulation. All the elements of the fingers are shown in Fig. 5c. Also, this figure shows the approximate quantity of rice required.

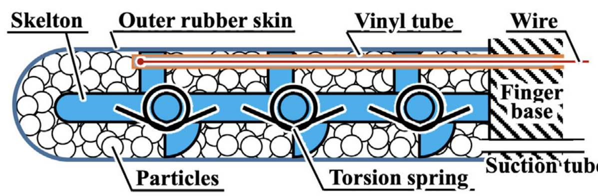
Some problems appeared while building the gripper. The first one was the difficulty of printing, building and attaching together all the pieces of the inner structure. Every piece must be designed and printed precisely to avoid movement friction between pieces, and a good quality 3D-printer is called for. Another problem is that some parts tend to break often during the grasping tests, requiring the whole finger to be rebuilt to continue with the experiments. The last problem was that the internal nylon tube failed due to friction; as a consequence, the vacuum encapsulation was lost, the finger had to be discarded, and the entire manufacturing process repeated.

3.3. Electric and pneumatic system

The motor used to pull the tendons in both gripper prototypes is a 12 V DC motor. Also a similar base for embedding the

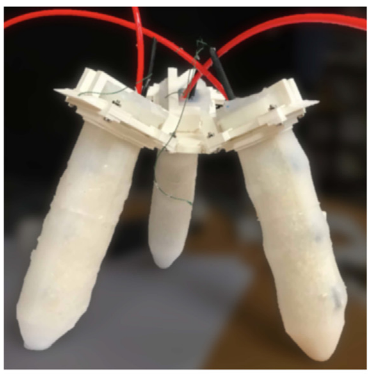


(a) Complete gripper

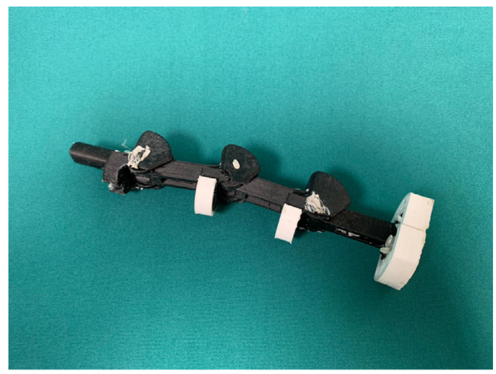


(b) Finger inner structure

Fig. 4 Original Mizushima VS gripper. Image and figure from [8].



(a) Gripper based in [8]



(b) Finger inner structure

(c) Parts of the finger

Fig. 5 Our three-fingered adaptation of the Mizushima VS gripper.

motor, adapted to the gripper bases, has been 3D printed for both gripper models. The finger tendons are attached to a pulley that is welded into the shaft of the motor and calibrated in such a way that the three fingers move concurrently to perform a grasp.

The same actuators and control architecture are used in both gripper prototypes. An Arduino board with a DC motor driver is used to control the DC motor that moves the tendons of both grippers (Fig. 6). The motor driver can control up to two DC motors though only one is controlled in this application. Two buttons are installed to perform an open-close action in the gripper without the need of a computer.

The pneumatic system is composed of an air pump with a pressure switch, which provides the system with air at the desired pressure. The pump is connected to a 2/2 valve that is used to open or close the system when it is needed. The vacuum into the silicone core is applied by a Venturi tube. Then, the vacuum produced is divided and applied into the finger cavities. The scheme of the pneumatic system can be observed in Fig. 7.

Fig. 8a shows the relationship between the negative pressure inside the finger depending on the main positive pressure, extracted from [32]. Four stiffness states are defined for both grippers at $0bar, 1bar, 3bar$ and $5bar$ of positive pressure

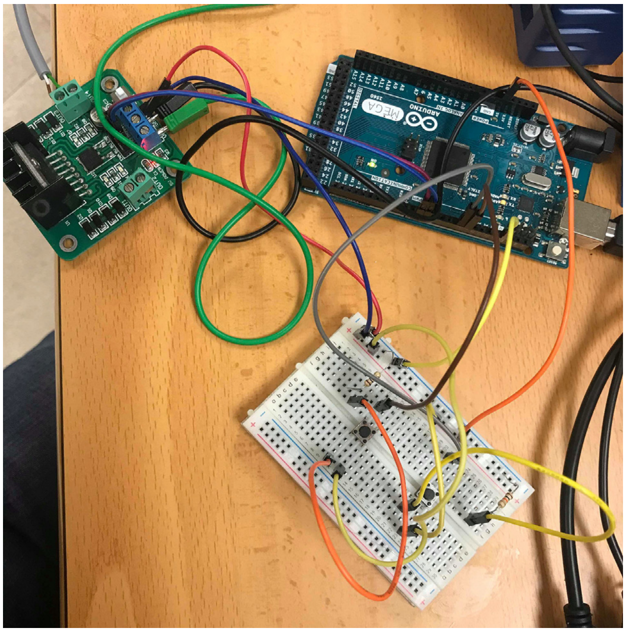


Fig. 6 Electric components for control.

applied in the Venturi tube. These states correspond to a series of positive and negative pressures shown in Fig. 8b.

4. Experiments

We have designed several protocols and tests to analyze the variable-stiffness prototype grippers described in the previous sections. These benchmarks have been inspired in the methods proposed by other researchers to measure the performance of grippers. Five benchmark tests are described in this section. The purpose of a benchmark is to experimentally evaluate a certain property or functionality of a device or algorithm and provide a numerical outcome of the performance that can be used for comparison or ranking with similar devices. In order to be useful a benchmark protocol must define the setup, conditions and procedure in which the experiments should be done, along with the metrics that will be used for measuring. Both, the setup and the metrics must be independent of the subjects to be benchmarked.

For the implementation of three out of the five tests we built a specific test bench. It consists of a supporting platform that allows to rigidly attach the gripper with the palm facing downwards. Most of the benchmark tests assume a top-down grasp approaching direction. The gripper must be held at a sufficient height so that neither it nor the held object touch the floor. Fig. 9 shows our test bench and a detail of the Mizushima VS gripper attached to it.

4.1. Object grasping test

The aim of the object grasping test is to measure empirically how many objects can the gripper grasp depending on how the stiffness of its fingers is changed. This test also estimates to which extend the design of the gripper is efficient enough to grasp a wide range of objects, even without changing the stiffness.

The gripper must be attached in a fixed position with the fingers pointing downwards to grasp the objects from the top. In this position the fingers should be able to move freely. Fig. 9 shows the required setup with the two gripper prototypes in the testing position. The target object is placed over a stand with adaptable height, so that it can be easily reached by the gripper fingers. The gripper must be placed above the object where it can perform a cylindrical grasp by just activating it.

The objects selected for the adaptation analysis have been chosen from the kitchen subset of the YCB Benchmark set [33], due to the variety of objects contained in that set. There are some heavy objects, such as the Windex glass cleaner bottle, objects that generate large grasping torques, such as the cooking skillet, and deformable objects, as the table cloth. For each object a standing and grasping point has been defined. The standing position describes how the object will be presented to the gripper before closing it, and the grasping point indicates the part of the object where it will be grabbed. The items are shown in Fig. 10a, and the grasping configurations are described in Fig. 10b.

For each object and the stiffness states in Fig. 8b the experimental protocol follows these steps:

1. Object is placed on the stand and set up so that the gripper can easily grasp it when activated.
2. Gripper is activated in softest state.
3. Object is grasped.
4. Stiffness is changed to the desired state (if the determined state is the softest one, nothing changes).
5. Stand is removed.
6. Hold for 5 s.
7. Object is released.

The grasp is considered successful if the object remains firmly held from the moment the gripper is activated. Each case is repeated five times for each object and stiffness state. If during one of these attempts the grasp fails, the whole five attempts are considered as a failure too.

4.2. Finger Force test

The aim of this test is to measure the finger force in all the stiffness states. This test is based on the Finger Strength test pro-

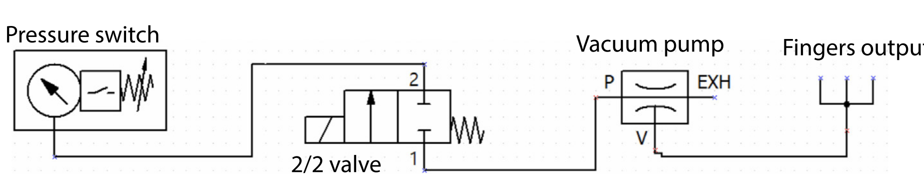
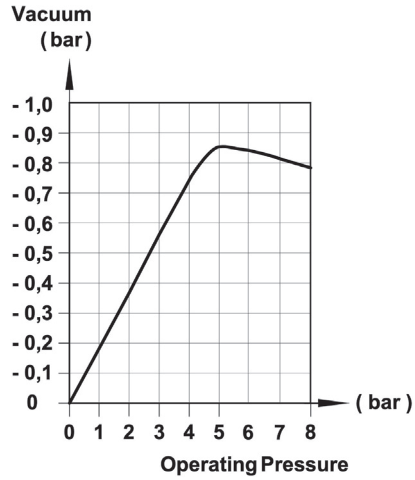


Fig. 7 Pneumatic scheme.

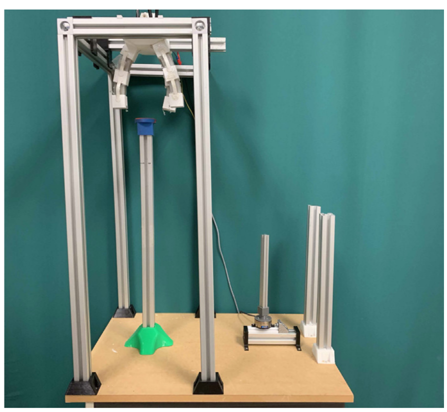


(a) Negative pressure (vacuum) produced by the operating pressure through the Venturi tube. Graph extracted from [32]

State	Positive	Negative
State 1	0 bar	0 bar
State 2	1 bar	-0.175 bar
State 3	3 bar	-0.55 bar
State 4	5 bar	-0.85 bar

(b) Stiffness states

Fig. 8 Vacuum parameters.



(a) RobInLab VS gripper at the test bench

(b) Detail of the test bench with Mizushima VS gripper

Fig. 9 Structure of the test bench used for several benchmark tests with the gripper prototypes attached to it.

posed by the National Institute of Standards and Technology (NIST) [34]. However, a modification has been introduced in order to consider specific properties of the variable-stiffness mechanism.

A force-torque sensor (Schunk model FTN-Mini-45) is used to obtain the force data. It is attached to a linear guide at one side and to a rod on the other with a 3D-printed piece. The gripper must be attached in a fixed position perpendicular to the ground and able to move freely to adapt to the rod. This setup can be observed in Fig. 11.

The linear guide in which the sensor is screwed is also inserted into a rod which is fixed on the ground, in such a way that its z axis corresponds to the normal direction to the ground plane. The linear guide is allowed to move freely along the rod so that it can be easily adjusted to the finger length. The gripper is mounted in a support, composed of two aluminium profiles parallel to each other. This configuration allows the fingertip to contact perpendicularly the end of the rod. In the initial position the fingertip touches the rod without exerting any force. After the initial adjustments the finger and rod positions must be fixed at the beginning of the tests to prevent false lectures due to the displacement of the gripper or the rod.

For each of the stiffness states mentioned in Fig. 8b the protocol follows these steps:

1. Start recording the sensor readings.
2. The gripper is activated and the rod is pushed.
3. Hold for 5 s.
4. Gripper is turned off.
5. Stop recording the sensor readings.

The result of the measurements is a graph with the evolution of the force during the recording of the whole experiment.

4.3. Grasp strength test

The purpose of this part of the benchmark is to determine two characteristics of the gripper: first, the inner strength that the grasped objects are suffering at a grasping cycle, and second,

(a) Kitchen items from the YCB Benchmark

Object	Standing position	Grasping point
Pitcher	Handle face up	Handle
Bleach cleanser	Label face up	Bottle middle
Glass cleaner	Label face up	Bottle middle
Plastic wine glass	As in fig. 10a	Glass mouth
Metal bowl	As in fig. 10a	Bowl mouth
Metal mug	As in fig. 10a	Mug mouth
Abrasive sponge	As in fig. 10a	Object middle
Cooking skillet	As in fig. 10a	Handle
Metal plate	Stand perpendicular	Plate border
Eating utensils	As in fig. 10a	Handle
Spatula	As in fig. 10a	Handle
White table cloth	As in fig. 10a	Object middle

(b) Grasping configurations for each object

Fig. 10 Objects and configurations used in the grasping test.

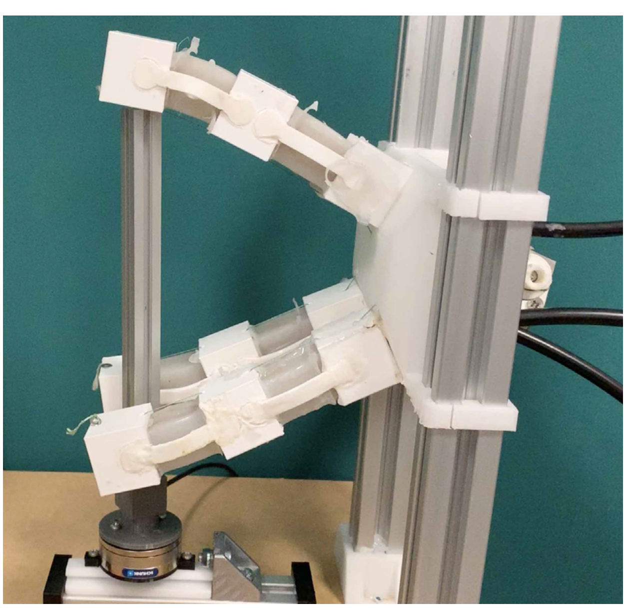


Fig. 11 Finger force set up.

how the dynamic change of stiffness during the grasp affects the object.

A special artifact has been constructed to gather data for the test. The artifact is a sensorized cylinder similar to the one proposed by the National Institute of Standards and Technology (NIST) [34] for the Grasp Strength test. It has been modified to embed a different type of sensor. The artifact consists of a cylinder with a force cell in its interior. Fig. 12 shows a picture and its schematic representation. It is composed of three parts:

- Two semi-cylinders made of PLA.
- A force-torque sensor (Schunk model FTN-Mini-45), the same one used for the finger force test described in Section 4.2.

The gripper must be attached in a fixed position parallel to the ground that is high enough to let the gripper move freely (around 75 cm should be enough). This is the same setup as in the *Object grasping test*, described in Section 4.1.

The artifact is placed over a stand at a reaching and comfortable distance of the gripper to allow a cylindrical grasp. The test consists in activating the gripper to grasp the cylinder during a short period of time and recording the sensor readings for all the different stiffness states of the gripper.

For each of the stiffness states mentioned above the following steps are performed:

1. The artifact is placed over the stand and set up so that the gripper can easily grasp it when activated.
2. Start recording the sensor readings.
3. The gripper is activated and the cylinder is grasped.
4. Hold the cylinder for 5 s.
5. The cylinder is released.
6. Stop recording the sensor readings.

Again, the resulting measurements are a graph with the evolution of the force during the complete recording of the experiment for each stiffness state.

4.4. Gripper payload test

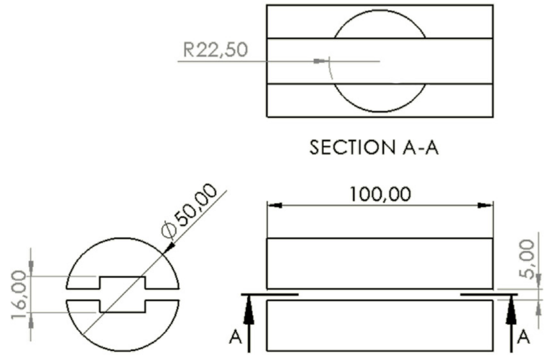
The fourth test measures the gripper payload, that is, the maximum weight that it is capable to hold after grasping with the different stiffness states without a failure.

It consists in grasping a basket with a 3D-printed handle for the gripper to grab it easily. The whole set has a total weight of 340gr when empty, (see Fig. 13a). The gripper holds the cylinder from the top. The handle cylinder's dimensions are 60 mm of diameter per 180 mm of length.

Initially the basket is grasped empty, if the try is successful and the basket does no fall, a plastic bottle filled with water that weights 335gr in total is added to the basket. The process is repeated until a grasp failure happens. The annotated payload will correspond to the last before the failure. There is a total of 12 bottles of water of 330 ml., each one weighting 335gr.

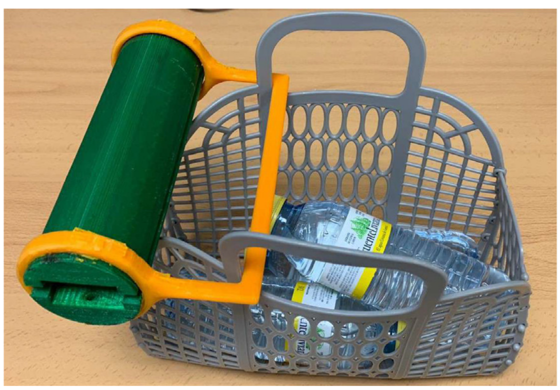
Here is protocol followed for or each stiffness state and weight:

(a) Cylinder artifact



(b) Schematic representation

Fig. 12 Grasping force cylinder.

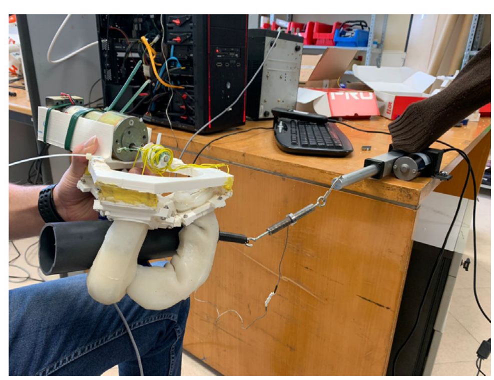


(a) Basket used for payload test with bottles

(b) Grasping the basket

Fig. 13 Payload test basket and grasping method.

(a) Slip Resistance elements

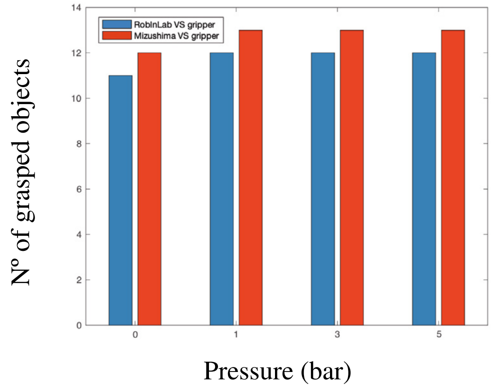


(b) Slip Resistance setup

Fig. 14 Slip Resistance elements and setup.

1. The basket is manually placed below the gripper so that it can be grasped.
2. Grasp is done, as in Fig. 13b.
3. Release the manual hold on the basket.
4. Hold for 5 s.
5. The grasp is released.

The grasp is considered successful if during the five seconds of the test the basket does not escape from the grasp

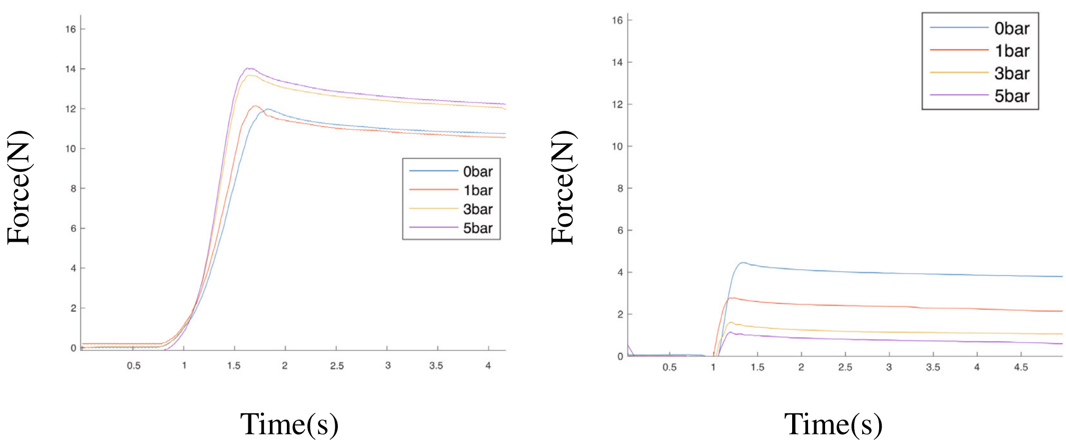


(a) Test graphic

Pressure	RobInLab	Mizushima
0bar	11 objects	12 objects
1bar	12 objects	13 objects
3bar	12 objects	13 objects
5bar	12 objects	13 objects

(b) Test measures

Fig. 15 Results of object grasping test.



(a) RobInLab VS gripper (b) Mizushima VS gripper

Fig. 16 Results for the finger force tests.

of the gripper. For each gripper stiffness state the test is repeated five times, and the result will be the lowest score of the five.

4.5. Gripper Slip Resistance

This test has also been taken from the NIST grasping benchmarks. The purpose of this experiment is to get continuous force readings using an actuator and loadcell, determining more accurately the peak load, i.e. the maximum external force applied to an object that the gripper is able to withstand before slipping whilst grasping it.

A loadcell is used to read the force values. This loadcell is attached to a cylinder at one end, and to a linear actuator at the other. The cylinder has a 50 mm diameter. These elements are shown in Fig. 14a.

The gripper grasps the cylinder and then the sensor is set to start reading force values, at that moment the linear actuator starts retracting so that an external force is exerted on the cylinder, which is counterbalanced by the grasping force, as seen on Fig. 14b. When the cylinder starts slipping from the gripper the linear actuator is stopped and the sensor has measured the peak load.

The test sequence is as follows:

1. The cylinder is grasped by the gripper.
2. The linear actuator is activated.
3. When the cylinder starts to slip from the grasp the linear actuator is stopped.
4. During all the process the force is being measured.

The test is repeated ten times for each gripper in its softest state, then the mean maximum force and the confidence values will be calculated.

5. Results and discussion

The five benchmark tests were used to evaluate and compare the RonInLab VS and Mizushima VS grippers. In this section we present the results along with a discussion. The results of each test will be explained and discussed separately for a better understanding.

5.1. Object grasping test

Fig. 15 shows the results for the object grasping test. The graph shows the number of grasped objects for each stiffness state for both grippers.

From the results it can be seen that the Mizushima VS gripper slightly improves the performance of RobInLab VS gripper. The difference is only one object that slipped from RonInLab VS gripper due to the lower friction coefficient of the 3D-printed phalanges of the RobInLab VS gripper. It could be improved by applying a softer silicone layer on top of the parts so that the material touching the object is silicone instead of plastic, as it is the case for the Mizushima VS gripper.

5.2. Finger force test

Fig. 16a and b show the results of the finger force test for the RonInLab gripper and Mizushima VS gripper, respectively. This test measures the variation of the force deployed by an individual finger for each of the stiffness states.

The results indicate that the RobInLab VS gripper produces considerably higher forces in all the stiffness states, in the range of 10–12 N after stabilization. Actually, some pair of states are almost indistinguishable (0 and 1 bar, and 3 and 5 bar). The explanation for this phenomenon is that probably the tendon mechanism, activated during the whole test, is exerting a constant and predominant force. The activation force adds some more force. On the contrary, the Mizushima VS gripper presents lower force values but more clearly differentiated. In this case the influence of the tendon mechanism is lower.

Both grippers perform in a antagonist way, however the RobInLab VS gripper increments the finger force for higher stiffness states, whereas it is the other way for the Mizushima VS gripper, it gets decreasing values of the finger force for the stiffest states.

These results illustrate the main differences resulting from the configurations adopted on each gripper.

5.3. Grasp strength test

Results for the grasp strength test are shown in Fig. 17a and b for the RobInLab VS gripper and Mizushima VS gripper, respectively. In both cases, the exerted force stabilizes at the same level for all the stiffness states. There is a clear difference between both grippers in their final level. The RobInLab VS gripper can maintain a force of ~35 N, around five times higher than that of the Mizushima VS gripper, (~7 N).

5.4. Gripper payload test

Results for the payload test for both grippers are shown in Fig. 18. This test analyses the variation of the weight that the gripper can lift in all stiffness states.

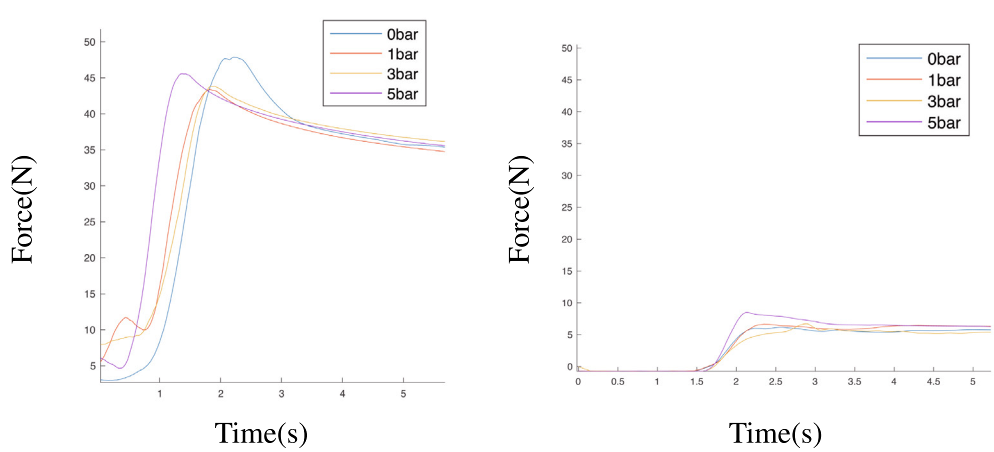
These results show that the fingers can withstand more weight as the stiffness state is increased. Since the grippers have two actuation systems, the principal one by means of a DC motor and tendons, and the secondary one based on vacuum and jamming, the test was done deactivating the DC motor when the basket was grasped, and then waiting 5 s. This means that the weight of the objects in the basket was only supported by the stiffness of the fingers itself. This was done for all the cases.

As it can be seen the RobInLab VS gripper can lift around 1 kg more than the Mizushima VS gripper in all the stiffness states. The phalanges provide the RobInLab VS gripper with a more solid structure and, as a consequence, the capability to maintain the fingers shape under high external forces.

5.5. Gripper slip resistance

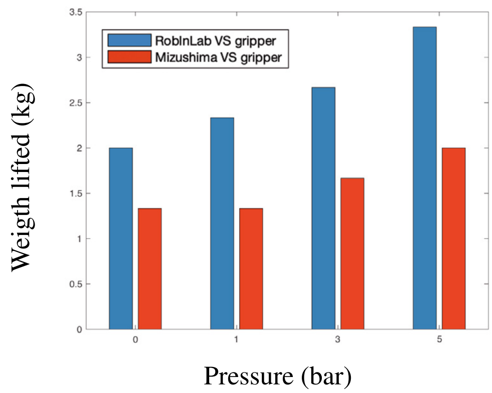
The results of the Slip Resistance test are summarised in Table 1. This test analyses the maximum external force applied to an object that the gripper can withstand before the object slips away from the gripper while grasped.

The table results show that the RobInLab VS gripper can withstand a considerably higher peak load than the Mizushima VS gripper, even surpassing it by 100%, i.e. the RobInLab VS gripper can double the peak load of the Mizushima VS grip-



(a) RobinLab VS gripper (b) Mizushima VS gripper

Fig. 17 Results for the grasp strength tests.



(a) Test graphic

Pressure	RobInLab	Mizushima
0bar	2kg	1.33kg
1bar	2.33kg	1.33kg
3bar	2.67kg	1.67kg
5bar	3.33kg	2kg

(b) Test measures

Fig. 18 Results for the payload tests.

per, being clearly a better alternative according to this benchmark.

In Fig. 19 the sensor readings for all the tests are shown, exposing how the force rises until the slipping moment, where it starts to decrease because the gripper is not grasping it properly as the cylinder has slipped away from the grasp.

6. Conclusions

The ability of soft grippers to adapt to a large variety of object shapes is obtained by paying the price of a diminished grasping force. Novel variable-stiffness gripper designs try to reconcile these two apparently contradictory design goals, that is, keep that adaptability but increase that force.

The main contribution of this paper is the design and analysis of a variable-stiffness gripper that not only complies with state-of-the-art requirements in terms of a good response time for stiffness change, lack of external elements and no generation of inner stress, but also combines a good adaptability with a significantly higher grasping force. As a second contribution we have presented the design and implementation of a set of five benchmark tests specifically oriented to variable-stiffness grippers aimed at measuring that intended ability to adapt to different shapes together with the different forces it can exert (object grasping, finger force, grasp strength, gripper payload and slip resistance).

The RobInLab VS gripper is composed of an inner silicone core filled with ground coffee, embedded into an outer 3D-printed structure, which configures and supports the inner core. With the purpose of comparison, a second prototype gripper, adapted from model [8] and with similar design principles, has also been manufactured, the Mizushima VS gripper. Both grippers have been evaluated with our new set of benchmark protocols.

The results of the tests clearly show that the RobInLab VS gripper is able to exert considerably higher forces that the Mizushima VS gripper without a reduction in its shape adaptability. To understand the importance of these results it is necessary to consider the process of grasping an object. This is basically divided in two phases, a first one in which the gripper makes contact and adapts gently to the shape of the object, and the second one, after completing the closure, in which the gripper must be able to firmly hold the grasped object for the transportation or the task at hand. For the first phase, the combination of tendon driven mechanisms and the softness of the jamming core make both grippers highly adaptable to different object shapes. However, for the second phase, a greater holding force is helpful to avoid dropping the object. In this sense, our experiments suggest that the new RobInLab VS gripper design performs at a much higher level in the finger force, grasp strength, gripper payload, and slip resistance tests. In addition, our experience in the construction of both grippers points out that our implementation is simpler and more robust, as mentioned in Section 3.2. We can then conclude that our solution significantly outperforms previous approaches using similar variable stiffness designs.

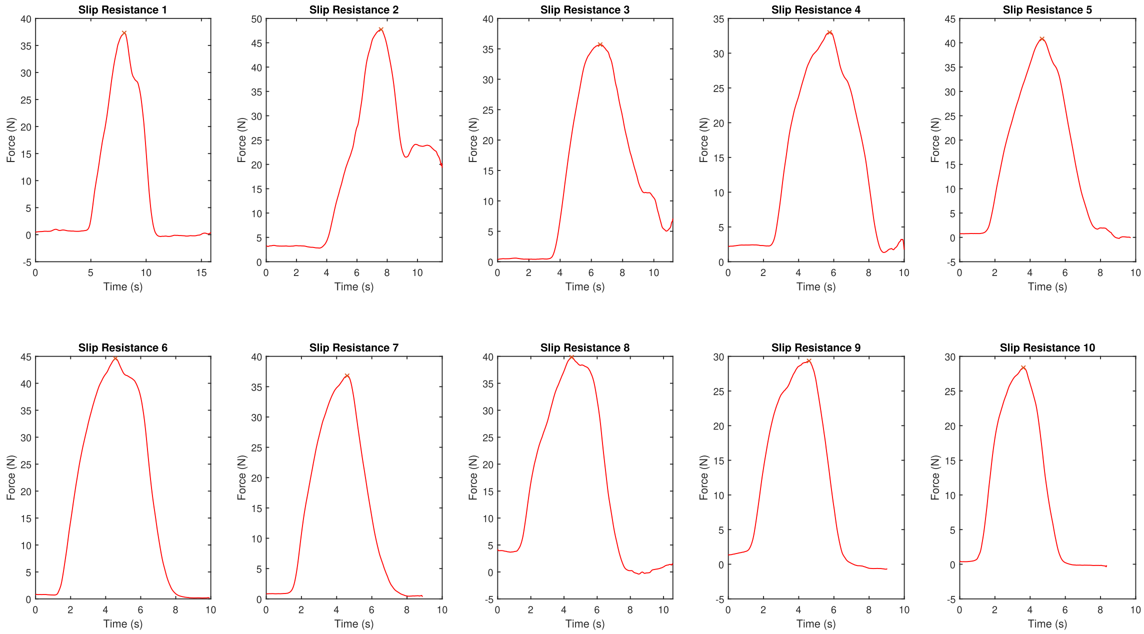
Future improvements of the prototype include making it smaller by reducing the volume of the current fingers, or adding elements such as nails in order to improve its aptitude for precision grasps. With this enhancements we will start testing the new grippers with additional objects from the YCB set. The aim will be to succeed in grasping the maximum number of objects with just the same gripper by changing the stiffness or the grasping mode and strategy.

Table 1 Slip Resistance results.

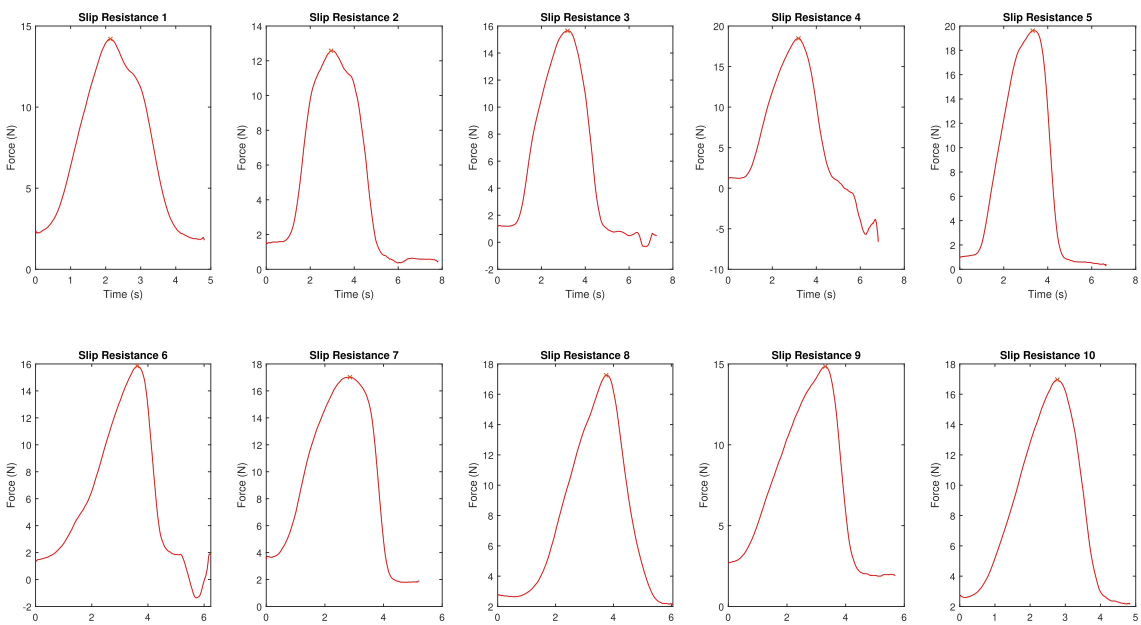
Gripper	Mean Peak Load	Sup Confidence	Inf Confidence
RobInLab VS gripper	37.34 N	41.77 N	32.91 N
Mizushima VS gripper	16.24 N	17.74 N	14.76 N

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.



(a) RobInLab VS gripper



(b) Mizushima VS gripper

Fig. 19 Sensor readings for the Slip Resistance test for both grippers.

Acknowledgements

This paper describes research conducted at UJI Robotic Intelligence Laboratory. Support for this laboratory is provided in part by Ministerio de Ciencia e Innnovación (DPI2015-69041-R and DPI2017-89910-R), by Universitat Jaume I (UJI-B2018-74), and by Generalitat Valenciana (PROMETEO/2020/034).

References

[1] A. Rodić, B. Miloradović, S. Popić, S. Spasojević, B. Karan, Development of modular compliant anthropomorphic robot hand, in: Mechanisms and Machine Science, vol. 16, Springer, Cham, 2014, pp. 205–219. doi:10.1007/978-3-319-01592-7_15.

[2] D. Rus, M.T. Tolley, Design, fabrication and control of soft robots (May 2015). doi:10.1038/nature14543.

[3] R. Pfeifer, M. Lungarella, F. Iida, Self-organization, embodiment, and biologically inspired robotics (Nov 2007). doi:10.1126/science.1145803.

[4] R. Pfeifer, M. Lungarella, F. Iida, The challenges ahead for bio-inspired 'soft' robotics, Commun. ACM 55 (11) (2012) 76, https://doi.org/10.1145/2366316.2366335, URL http://dl.acm.org/citation.cfm?doid=2366316.2366335.

[5] S.I. Rich, R.J. Wood, C. Majidi, Untethered soft robotics, Nature Electron. 1 (2) (2018) 102–112, https://doi.org/10.1038/s41928-018-0024-1.

[6] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendo, F. Iida, Soft Manipulators and Grippers: A Review, Front. Robot. AI 3 (2016) 69, https://doi.org/10.3389/frobt.2016.00069.

[7] J.R. Amend, E. Brown, N. Rodenberg, H.M. Jaeger, H. Lipson, A positive pressure universal gripper based on the jamming of granular material, IEEE Trans. Rob. 28 (2) (2012) 341–350, https://doi.org/10.1109/TRO.2011.2171093.

[8] K. Mizushima, T. Oku, Y. Suzuki, T. Tsuji, T. Watanabe, Multi-fingered robotic hand based on hybrid mechanism of tendon-driven and jamming transition, in: 2018 IEEE International Conference on Soft Robotics, RoboSoft 2018, IEEE, 2018, pp. 376–381, https://doi.org/10.1109/ROBOSOFT.2018.8404948.

[9] Y. Hao, T. Wang, X. Fang, K. Yang, L. Mao, J. Guan, L. Wen, A variable stiffness soft robotic gripper with low-melting-point alloy, in: Chinese Control Conference, CCC, IEEE, 2017, pp. 6781–6786, https://doi.org/10.23919/ChiCC.2017.8028427.

[10] Y. Yang, Y. Chen, 3D printing of smart materials for robotics with variable stiffness and position feedback, in: IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM, IEEE, 2017, pp. 418–423, https://doi.org/10.1109/AIM.2017.8014053.

[11] A.H. Memar, N. Mastronarde, E.T. Esfahani, Design of a novel variable stiffness gripper using permanent magnets, in, in: Proceedings - IEEE International Conference on Robotics and Automation, IEEE, 2017, pp. 2818–2823, https://doi.org/10.1109/ICRA.2017.7989328.

[12] A. Firouzeh, J. Paik, An under-actuated origami gripper with adjustable stiffness joints for multiple grasp modes, Smart Mater. Struct. 26 (5) (2017) 055035, https://doi.org/10.1088/1361-665X/aa67fd.

[13] M. Manti, V. Cacucciolo, M. Cianchetti, Stiffening in soft robotics: A review of the state of the art, IEEE Robot. Autom. Mag. 23 (3) (2016) 93–106, https://doi.org/10.1109/MRA.2016.2582718.

[14] D. Cardin-Catalan, A.P. del Pobil, A. Morales, Analysis of variable-stiffness soft finger joints, in: Advances in Intelligent Systems and Computing, vol. 867, 2019, pp. 334–345. doi:10.1007/978-3-030-01370-7_27.

[15] Z. Shahid, A.L. Glatman, S.C. Ryu, Design of a Soft Composite Finger with Adjustable Joint Stiffness, Soft Robot. 00 (00) (2019) 1–11, https://doi.org/10.1089/soro.2018.0148.

[16] A. Firouzeh, J. Paik, Grasp mode and compliance control of an underactuated origami gripper using adjustable stiffness joints, IEEE/ASME Trans. Mechatron. 22 (5) (2017) 2165–2173, https://doi.org/10.1109/TMECH.2017.2732827.

[17] J. Li, M. Sun, Z. Wu, H. Yin, Design, analysis, and grasping experiments of a novel soft hand: Hybrid actuator using shape memory alloy actuators, motors, and electromagnets, Soft Robotics 7 (3) (2020) 396–407, pMID: 31905330. doi:10.1089/soro.2018.0123.

[18] M.K. Brown, A controlled impedance robot gripper, AT T Technical J. 64 (4) (1985) 937–969, https://doi.org/10.1002/j.1538-7305.1985.tb00021.x.

[19] F.J. Abu-Dakka, L. Rozo, D.G. Caldwell, Force-based variable impedance learning for robotic manipulation, Robot. Auton. Syst. 109 (2018) 156–167, https://doi.org/10.1016/j.robot.2018.07.008, http://www.sciencedirect.com/science/article/pii/S0921889018300125.

[20] R. Martín-Martín, M.A. Lee, R. Gardner, S. Savarese, J. Bohg, A. Garg, Variable impedance control in end-effector space: An action space for reinforcement learning in contact-rich tasks (2019). arXiv:1906.08880.

[21] A. Dutta, G. Obinata, Impedance control of a robotic gripper for cooperation with humans, Control Eng. Practice 10 (4) (2002) 379–389, mechatronics. doi: 10.1016/S0967-0661(01)00152-6. http://www.sciencedirect.com/science/article/pii/S0967066101001526.

[22] B. Vanderborght et al, Variable impedance actuators: A review, Robot. Auton. Syst. 61 (12) (2013) 1601–1614.

[23] A. Billard, On the mechanical, cognitive and sociable facets of human compliance and their robotic counterparts, Robot. Auton. Syst. 88 (2017) 157–164.

[24] Y. Okatani, T. Nishida, K. Tadakuma, Development of universal robot gripper using MRαfluid, in: 2014 Joint 7th International Conference on Soft Computing and Intelligent Systems, SCIS 2014 and 15th International Symposium on Advanced Intelligent Systems, ISIS 2014, IEEE, 2014, pp. 231–235. doi:10.1109/SCIS-ISIS.2014.7044707.

[25] Y. Jiang, J.R. Amend, H. Lipson, A. Saxena, Learning hardware agnostic grasps for a universal jamming gripper, in, in: Proceedings - IEEE International Conference on Robotics and Automation, IEEE, 2012, pp. 2385–2391, https://doi.org/10.1109/ICRA.2012.6225049.

[26] A. Mo, W. Zhang, Pin array hand: A universal robot gripper with pins of ellipse contour, in: 2017 IEEE International Conference on Robotics and Biomimetics, ROBIO 2017, vol. 2018-Janua, IEEE, 2018, pp. 2075–2080. doi:10.1109/ROBIO.2017.8324725.

[27] S. Licht, E. Collins, D. Ballat-Durand, M. Lopes-Mendes, Universal jamming grippers for deep-sea manipulation, in: OCEANS 2016 MTS/IEEE Monterey, OCE 2016, IEEE, 2016, pp. 1–5. doi:10.1109/OCEANS.2016.7761237.

[28] Y. Li, Y. Chen, Y. Yang, Y. Wei, Passive Particle Jamming and Its Stiffening of Soft Robotic Grippers, IEEE Trans. Rob. 33 (2) (2017) 446–455, https://doi.org/10.1109/TRO.2016.2636899.

[29] L. Cen, A. Erturk, Bio-inspired aquatic robotics by untethered piezohydroelastic actuation, Bioinspirat. Biomimet. 8 (1) (2013) 016006, https://doi.org/10.1088/1748-3182/8/1/016006.

[30] M. Cianchetti, V. Mattoli, B. Mazzolai, C. Laschi, P. Dario, A new design methodology of electrostrictive actuators for bio-inspired robotics, Sensors Actuators, B: Chem. 142 (1) (2009) 288–297, https://doi.org/10.1016/j.snb.2009.08.039.

[31] M. Cianchetti, M. Follador, B. Mazzolai, P. Dario, C. Laschi, Design and development of a soft robotic octopus arm exploiting embodied intelligence, in, in: Proceedings - IEEE International Conference on Robotics and Automation, IEEE, 2012, pp. 5271–5276, https://doi.org/10.1109/ICRA.2012.6224696.

[32] Vacuum Pump spreadsheet, https://bit.ly/2ySIEAe, accessed: 2020-04-29.

[33] B. Calli, A. Walsman, A. Singh, S. Srinivasa, P. Abbeel, A.M. Dollar, Benchmarking in Manipulation Research: Using the Yale-CMU-Berkeley Object and Model Set, IEEE Robot. Automat. Mag. 22 (3) (2015) 36–52. arXiv:1502.03143, doi:10.1109/MRA.2015.2448951.

[34] J. Falco, K.V. Wyk, E. Messina, Performance Metrics and Test Methods for Robotic Hands doi:10.6028/NIST.SP.1227-draft.