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A Soft Variable Stiffness Gripper with Magnetorheological Fluids for Robust and Reliable Grasping

A. Pagoli¹, M. Alkhatib¹, Y. Mezouar¹

Abstract— This paper describes a new type of soft robotic grippers with variable stiffness to grasp efficiently a wide variety of objects. The gripper includes two sections, a pneumatic chamber for actuation and a tipping section for adjusting stiffness and shape adaptation. The tipping section consists of Magneto-rheological (MR) fluid, a magnetic source, and a tactile sensor. The MR fluid is responsible for changing the stiffness and it is solidified using the magnetic source which is a combination of magnetic elastomer, an electromagnet, and a permanent magnet. The tactile sensor is embedded within the soft finger to detect contact with the object and to trigger the magnetic source. Five experiments have been conducted to evaluate the gripper's performance, stiffness, and success rate. Results indicate that the proposed soft gripper is an effective design that can ensure robust grasping of a wide variety of objects. Furthermore, the study demonstrates that our design can change stiffness in less than one millisecond while increasing the applied force by approximately 2.5 times. In addition, by matching the fingertip to the shape of the object, the gripper exhibits a high success rate (more than 85%) ensuring reliable and secure grasping when the MR fluid solidifies.

Index Terms— Magnetorheological fluid, soft robotics, variable stiffness, soft pneumatic gripper, reliable grasping.

I. INTRODUCTION

The design of robot grippers is extremely challenging when it comes to handling different types of objects, requiring a variety of innovative and advanced strategies for grasping. Industrial rigid grippers typically consist of rough materials like metals or plastics [1]. However, their versatility is limited, necessitating specific designs for deformable or delicate objects [2]. Accurate identification of contact forces in these grippers is crucial for preventing object damage. Moreover, achieving reliable and precise grasping with these grippers necessitates sophisticated sensors, complex actuator-elastic element arrangements, and explicit control systems [3]. Recent advancements in soft robotics have created new possibilities due to their exceptional ability to interact with humans and delicate objects [4]. Soft robotic technologies have been widely used in manipulation [5], locomotion [6], sensing [7], grasping [8], rehabilitation [9], and medical applications [10]. Soft grippers are made from compliant

materials with high deformability and energy-absorbing properties that allow them to grasp a wide variety of irregularly shaped and sized objects [11]. These characteristics provide several additional advantages, including safety, lightweight, high number of degrees of freedom (DOF), simple control methods, robustness to collision, fast design, and low-cost manufacturing [12].

While soft robots are making advancements in various fields, their widespread use, particularly in industries, is still limited due to constraints such as low stiffness variation and inadequate load capacity. These limitations present new challenges for researchers [13]. In addition, soft grippers need to generate sufficient force based on the object's type, shape, and weight [14]. For example, a soft robot can reach organs in minimally invasive surgery, but it is not rigid enough to apply significant force to the target or to support the weight of the organ [15]. Using stiffness control allows a variety of external loads to be carried while maintaining manipulation flexibility. Variable stiffness techniques are therefore of great interest in soft robots to deal with a wide range of external loads [16]. Addressing these gaps will enhance the capabilities of soft actuators and expand their applications without compromising their ability to handle different object types. Moreover, a variable stiffness of the gripper can allow it to be adapted to the shape of an object by applying the appropriate force.

Various approaches have been studied to incorporate variable stiffness into flexible grippers. These approaches can be categorized into four main groups based on their operating principles [16]: 1) Shape memory materials (SMMs); 2) Low melting-point materials (LMPM); 3) Jamming based methods; 4) Electro or magneto-rheological fluids (ER/MR). Within these groups, stiffness is modified by leveraging changes in materials' intrinsic properties through the application of thermal or electric energy, chemical reactions, or electromagnetic fields [17].

SMMs can be classified into two main groups: Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs). Heating SMMs above the glass transition temperature allows their elasticity to be transformed from a temporary shape to a memorized permanent shape [18]. SMAs exhibit a relatively small stiffness change ($\sim 4\times$) [19], whereas SMPs exhibit a significant relative stiffness change ($\sim 100\times$) [20]. External heaters are required to heat SMPs [21]. In addition, low recovery speed, difficult controllability, hysteresis, and lack of accuracy are the main drawback of using SMMs [22]. LMPMs, including Low melting point alloys (LMPAs) and Low melting point polymers (LMPPs), have been utilized in soft robots to achieve significantly higher levels of stiffness variation ($\sim 1000\times$) [20]. Like SMPs, the main concern with LMPMs is the transition time.

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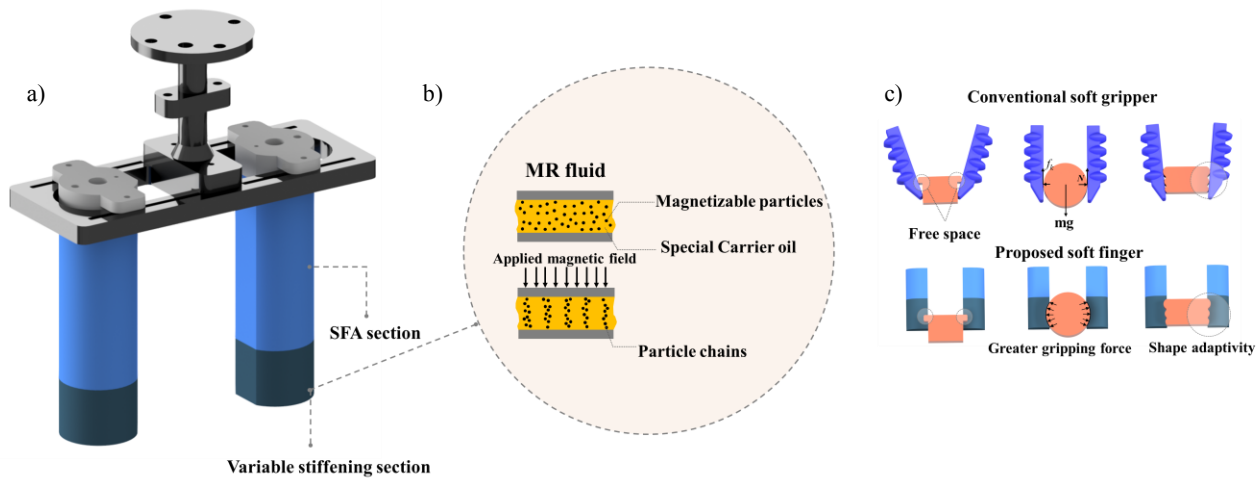


Figure 1. Working principle and schematic view of the proposed gripper. (a) The gripper consists of two sections: 1. Pneumatic actuator with embedded chamber 2. The stiffness section controls the stiffness of the finger by changing the alignment of the magnetic particles. (b) By applying a magnetic field to the MR fluid, particles within the fluids are aligned toward the MR fluid. (c) The proposed gripper can adapt itself to objects' shape in soft mode and grasp and hold it in the rigid mode, greatly enhancing the performance of grasping and ensuring secure gripping.

Depending on the size and geometry, the melting time of LMPMs varies from 1 to 30 s, while cooling takes more than 60 s [23]. A concern is that it is difficult to seal LMPMs to prevent leakage when they are in a liquid state [24]. Jamming-based approaches, including granular jamming methods (GJMs) and layer jamming methods (LJMs), offer new possibilities. In particular, they can improve the ability to vary the stiffness [25] and allow the shape of the finger to be adapted to the object being grasped [26]. The air is evacuated inside the gripper's membrane, which is filled with particles, thereby squeezing the particles together and increasing the stiffness of the gripper. Even though GJMs have promising features such as fast response and significant variation in stiffness, it requires a large volume of granular material to achieve significant stiffness change, which in turn requires large actuators and makes scaling up very challenging [26]. In LJMs, the friction between the layers of the stack can be modified using vacuum or electrostatic force to achieve the desired rigidity [27]. However, most developed LJMs are designed to bend only in one direction and cannot produce complex deformations. In addition, both of the mentioned jamming methods increase the initial stiffness which is not always desired [28].

ER, and MR fluids have recently been developed to control the stiffness of soft robots [29], [30]. ER fluids contain micrometer-scale polarizable particles in a dielectric fluid such as oil. The principle of operation is to modify their rheological properties by exposure to an electric field, which then results in a change in stiffness [31]. The change in rheological properties of ER fluids requires high electric fields that can be hazardous to humans. In contrast, in MR fluids, the alignment of magnetically permeable particles are responsible for varying stiffness with a stiffness variation range of 5 to 37 times [25], with a response time of less than 10 ms [20]. These characteristics make them an ideal choice for developing soft grippers with controllable variable stiffness and excellent response times. Therefore, in this work, we present a new soft pneumatic gripper with variable stiffness based on MR fluids. To achieve this, magnetic

elastomers are combined with electromagnets and permanent magnets, generating the necessary magnetic field to change the stiffness of the MR fluid. The proposed fabrication technique allows the easy construction of a soft gripper with different stiffness ranges that can be used for grasping various objects. In addition, the proposed hybrid design improves the payload capacity of the gripper as well as guarantees stable and reliable grasping without requiring a high current or huge electromagnet in contrast with the previous works [32]-[33]. Throughout the rest of the paper, the following structure is followed. First, a detailed description of the conceptual and structural design of the proposed gripper is provided. Then, the gripper's performance is demonstrated through several experiments. Finally, a discussion and conclusion are provided along with future work to be undertaken.

II. MATERIALS AND METHODS

While MR fluids hold significant potential, as discussed in the previous section, few studies have been conducted to use them for soft gripper construction. For instance, Pettersson et al. [33] developed and evaluated a novel robot gripper pouch filled with MR fluid for grasping natural food products, including apples, carrots, and broccoli. However, this gripper, while capable of providing the necessary compliance on the gripping surface, is bulky and has not been assessed for harvesting purposes. Nishida et al. [34] also proposed a similar ball-shaped structure consisting of an elastomeric container filled with MR fluid and an electromagnet. The disadvantage of the proposed gripper is that it can only be used to handle light objects, such as plastic containers, eraser, and tape. Recently, Koivikko et al. [35] presented a magnetically switchable soft suction gripper with MR fluid. The gripper can produce handling force of approximately 7 N with the 20 mm diameter soft suction cup. The main limitation of this gripper is the use of a large permanent magnet moved manually to achieve high magnetic intensity.

In this study, we suggest incorporating a layer of magnetic elastomer between the electromagnet and an MR fluid, along with an MR elastomer layer for the container, to enhance magnetic intensity. The proposed combination addresses a major limitation in using MR fluids for soft robot grasping applications by reducing both the size of the electromagnet and the required high current. Additionally, it leads to the development of a more compact soft gripper. A thin permanent magnet is also added to the electromagnet to increase the magnetic strength without a significant rise in voltage. Fig. 1 illustrates the proposed soft gripper design with two adjustable fingers. Each finger is made of silicone elastomer and consists of a pneumatic chamber as a soft fluidic actuator (SFA) section and an MR fluid incorporated at the fingertip of the finger as a stiffening section. The SFA section is responsible for the large stroke bending and applied forces. The stiffening section, on the other hand, oversees the shape adaptation and stiffness control of the gripper. The stiffening section consists of MR fluid, magnetic elastomers, and electromagnets. In addition, the MR fluid consists of 5–10 μm diameter micron-sized polarizable particles, usually iron (90% Fe), randomly dispersed in a carrier oil.

Fig. 1b illustrates the design and working principle of the proposed stiffening section. It consists of two phases: a soft phase and a rigid phase. For the soft phase, the magnetic field is not applied, the iron powders are randomly dispersed in oil, and the MR fluid acts as a simple fluid. For the rigid phase, the magnetic field is applied (by activating the embedded electromagnet) which changes the alignment of the magnetic iron particles gathered along the magnetic flux lines, forming a chain structure, and exhibiting a yield strength. By removing the magnetic field, the chain structures are crushed, and the MR fluid reverts to a fluid again, i.e., it returns to the soft phase. This material reacts very quickly to phase changes, less than 1 ms.

To grasp an object as shown in Fig. 1c, the SFA starts to bend toward the object by applying pressure inside the chamber without the magnetic field being activated. Simultaneously, the stiffening section conforms to the object with a soft phase where the gripper can adapt itself to the object's shape. A tactile sensor is embedded into the stiffening section to detect the contact point and the forces. Once this tactile sensor detects contact, the electromagnet is activated to solidify the MR fluid which controls the stiffness change. This increases the number of contact points and the force of grasping, while also controlling stiffness. In a conventional gripper, the object is grasped with a small contact area (Fig. 1c). However, in the proposed design, the gripper encompasses the object, which enhances the force distributed around the object. As a result of enlarging the contact area, the friction force has also increased, allowing the gripper to grasp the object with a more reliable and secure success rate. Hence, the proposed hybrid design of the SFA and the MR fluid helps to control the shape of the soft finger's tip by considering the shape of the object and enables stable grasping of a wide range of objects with non-uniform shapes.

The fabrication process of the proposed gripper is shown in Fig. 2. The procedure is simple and can be carried out in the following steps: 1) Manufacturing of magnetic elastomers

using a permanent magnet (Fig. 2a, Video S1); 2) Designing the molds for the two sections of the gripper (the SFA section and the stiffening section); 3) Molding the finger with silicone and magnetic elastomer 4) Injecting MR fluid and assembling the electromagnetic and sensor components.

To achieve a unified design, it is imperative to cast grippers step-by-step. In the first step, the magnetic elastomer is fabricated by crushing a permanent Supermagnet (NdFeB, grade N52, Supermagnet Co. [36]) into high magnetic permeability particles using a hammer or a ball milling machine (1 & 2 in Fig. 2a). Then a magnetic silicone mixture is produced by mixing the magnetic powders homogeneously with silicone liquids Eco-Flex 00-50 (recommended by ratio 1:1 between the curing agent and elastomer, Smooth on, USA) at a weight ratio of 1:10 (3 in Fig. 2a). However, the magnetic field produced by this mixture is weak because the magnetic particles are randomly aligned (4 in Fig. 2a). It is necessary to apply a strong external magnetic field to align the particles in the mixture. To achieve this, the mixture with an isolated mold with a cap is placed between two powerful permanent magnets (30 mm diameter, 30 mm height, NdFeB, grade N52, Supermagnet Co.) to produce a magnetic field with strengths of 0.45 T (4500 G) (5 in Fig. 2a). When the external magnetic field is removed after solidification at room temperature for five hours, the liquid mixture becomes a cured elastomer with a residual magnetic field from the aligned particles (Fig. 2a).

In the next step, a 3D printer is used to fabricate the molds (SFA mold and stiffening section mold) because of its precise and straightforward manufacturing capabilities. The SFA mold consists of three parts that make it extremely easy to remove the finger (gray color). Three hollow tunnels in the finger are designed to provide the following functions: 1) the pneumatic chamber (1 in Fig. 2b); 2) the electrical connections tunnel between the electromagnet and tactile sensor with the external control system (2 in Fig. 2b); 3) the MR fluid tunnel for injecting MR fluid into the stiffening section (pink color). On the other side, there are two parts to design the mold of the stiffening section; the right part has a cylinder shape for attachment of the electromagnet later; the left part has a small MR container that connects to the MR fluid tunnel in SFA (3 in Fig. 2b) for injecting MR fluid later. In the third step, Eco-Flex 00-50 is used because of its softness, high failure strain, and large elongation properties (~980%) [12] that make it appropriate for the proposed actuator design. This silicone liquid is poured into the SFA mold after being stirred well. This process produces air bubbles, which result in leaks within the structure. The air bubbles are therefore removed through vacuum degassing. During the curing of the SFA mold, the magnetic elastomer manufactured in step 1 is embedded in the middle of the stiffening section mold which is attached at the top of the SFA mold. Finally, a mixture of MR fluid and silicone is poured into the stiffening section mold. The potential challenge of using MR fluid with silicon is that the oil inside the MR fluid can be absorbed by the silicone affecting the performance of the gripper. To overcome this problem, MR fluid can be encapsulated in a very thin plastic pack and then implanted into the finger. Therefore, the proposed design not only enhances the field intensity but also increases the durability of the silicone. MRF- 140CG MR fluid

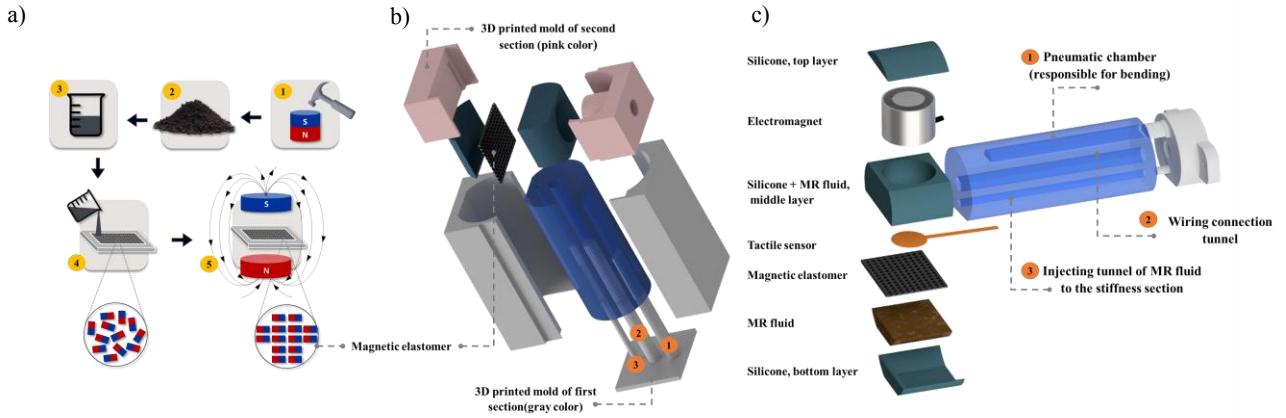


Figure 2. Manufacturing process of the proposed soft finger with variable stiffness at the fingertip. (a) The permanent magnets are crushed by hammers into tiny particles, then they are placed in the mold and mixed with a silicone polymer. A strong external magnetic field is used to align the magnetic poles of the composite, which, when removed after cure, leaves the composite with a magnetic field. (b) The soft pneumatic finger is built by pouring silicone into the first mold section (the grey one). The fabricated magnetic elastomer in the previous step is placed in the top mold (the pink one). To construct the second section, the mold is placed on top of the first mold, and mixed silicone liquid and MR fluid are poured into it. Before complete curing, the second part should be added to the top of the first part to achieve a unified finger. (c) An exploded view of the proposed finger consists of two main sections, SFA and stiffening part. The stiffening section includes an electromagnet, magnetic elastomer, MR fluid, and silicon layers.

(MRHCCS4-B with 80% Fe, Liquids corporation, UK) has been used for its excellent long-term sedimentation stability. It facilitates the redispersion of the magnetically permeable particles and prevents hard settling. A detailed view of the proposed finger is shown in Fig. 2. The stiffening section includes an electromagnet, magnetic elastomer, MR fluid, and silicon layers. After removing the finger from the molds, MR fluid is injected and encapsulated into the stiffness section (3 in Fig. 2b & 2c). Next, the electromagnet (20 mm in diameter with a height of 25 mm and powered by 24 V DC) and the tactile sensor (SingleTact Co. [37]) with a diameter of 15 mm and a maximum measured force of 45N are attached to the fingers. This sensor was selected because of its high flexibility, remarkable performance in detecting very small forces, and its ultra-thin design (~ 0.35 mm). The wiring connections between the electromagnet and the tactile sensor are placed inside the finger (2 in Fig. 2b & 2c).

III. RESULTS AND DISCUSSIONS

The proposed gripper has been designed to improve grasping capabilities for a wide range of objects using straightforward fabrication procedures and low-cost elastomer materials. To evaluate the proposed design, we fabricated a two-finger gripper with a total dimension of 160 mm in length (110 mm SFA section and 50 mm stiffening section) and 20 mm in diameter. The length of the pneumatic chamber is 90 mm. The movable design of the soft gripper handles allows the gripping opening to be adjusted between 1 millimeter and 10 millimeters. Based on our previous work [23]-[5] to reduce the ballooning effect, we designed the finger with a semi-circular cross-sectional chamber of 10 mm radius and a distance of 10 mm between this chamber and the outer diameter of the finger. For this gripper, the volume required to fill the MR fluid container in each finger is around 5 ml.

Different experiments were carried out to validate the performance of the proposed soft gripper. The first experiment aimed to evaluate the best trade-off between the applied magnetic field and the produced stiffness intensity.

In the second set of experiments, we evaluate the impact of the materials of the stiffening section on the stiffness. In the third set of experiments, the ability of the gripper to handle a variety of shapes and weights of objects is evaluated. In the fourth set of experiments, the performance of the stiffening section is studied with respect to the required force to grasp specific objects. Then, the effect of object shape on the performance of the soft gripper is investigated. Finally, the stiffening section is evaluated by showing its success rate during picking and placing objects several times.

In the first experiment, a variable magnetic field is applied to control the rate of stiffening produced by the solidification of the MR fluid. To generate the required magnetic field, several processes have been evaluated: different combinations of the permanent magnet, magnetic elastomer, and electromagnet under different voltages. Fig. 3a shows the measured relationship between the applied voltage and the magnetic field produced by the different combinations of magnetic sources. The produced magnetic field is measured using a Tesla meter (GM07, Hirst Magnetics). The magnetic field produced by an electromagnet (30 mm in diameter with a height of 30 mm) reached 103 mT at 24 V. This was not sufficient to solidify the MR fluid. To enhance the magnetic flux density without significantly increasing the voltage, we combined an electromagnet with a permanent magnet and magnetic elastomers. The magnetic field produced by the permanent magnet (20 mm diameter and 3 mm height, NdFeB, grade N52, Supermagnet Co.) is 40 mT. However, as can be seen in Fig. 3a, the combination of the electromagnet with the permanent magnet significantly increases the magnetic field to 120 mT at 24 V. The addition of the magnetic elastomer to this combination further increases the magnetic field to 140 mT. Based on visual observations of this experiment, upon reaching this level, the magnetic particles begin to move, causing the MR fluid to solidify and effectively changing the stiffness of the gripper.

However, the intensity of the magnetic field produced by the magnetic elastomer depends on the size and quantity of the

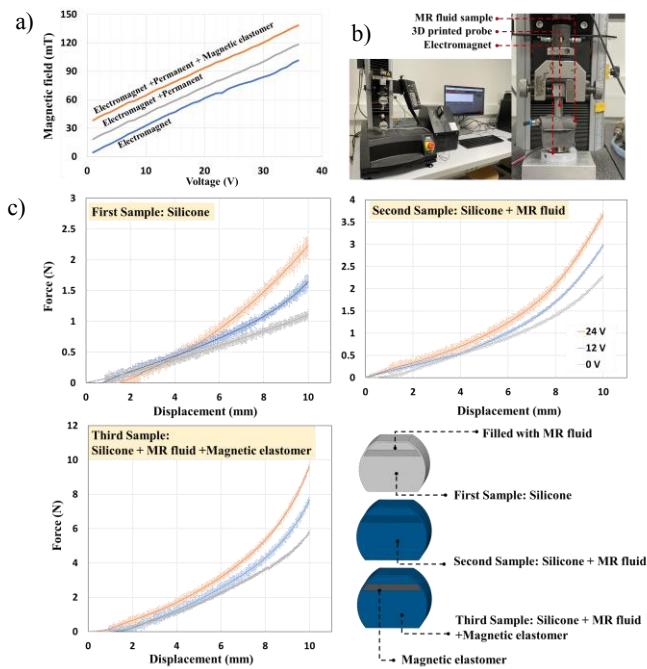


Figure 3. Experimental setup to evaluate the stiffness changes when the magnetic field is applied. (a) Maximizing the produced magnetic field with different combinations of an electromagnet with the permanent magnet and the magnetic elastomer. (b) An experimental mechanical setup (INSTRON 5543) was used to analyze the effectiveness of the proposed method for changing the stiffness. (c) To maximize the range of stiffness, three different samples were tested. Mixing silicone with magnetic fluid and utilizing magnetic elastomers at the tipping section of the finger allows to increase the stiffness range of the finger.

magnetic particles. Different samples have been tested to investigate the effect of the size of the magnetic particles. A ball mining machine produces finer particles with a lower magnetic characteristic (20 mT) than a hand crusher that produces particles coarser particles (30 mT). Furthermore, according to [38], As the magnetic field diminishes with distance from the electromagnet's surface, the magnetic elastomer's thickness should not exceed 2 mm to avoid adverse effects on the magnetic field, leading to a reduction in the total produced magnetic field effectiveness when interacting with the MR fluid.

In the second experiment, we evaluated the materials of the stiffening section to maximize the stiffness. Stiffness is measured by calculating the relationship between the applied force and the resulting displacement of the stiffening section. This means that a material has a higher stiffness when it requires higher applied forces to achieve the same displacement as another material with a lower force. Fig. 3b shows the experimental setup for the stiffness measurement. We use a universal testing machine (INSTRON 5543) to measure the force required for a given displacement. A combination of an electromagnet and a permanent magnet is used to generate the magnetic field. Several tests were performed on three different material samples: 1) Silicone alone; 2) Silicone with MR fluid; 3) Silicone with both MR fluid and magnetic elastomer. The first sample exclusively uses silicone to create the container. In the second sample, the container's fabrication involves mixing the MR fluid with uncured silicone. The third sample follows the same procedure as the second but introduces a magnetic elastomer layer at the container's base. As it is shown in Fig. 3b, a 3D-

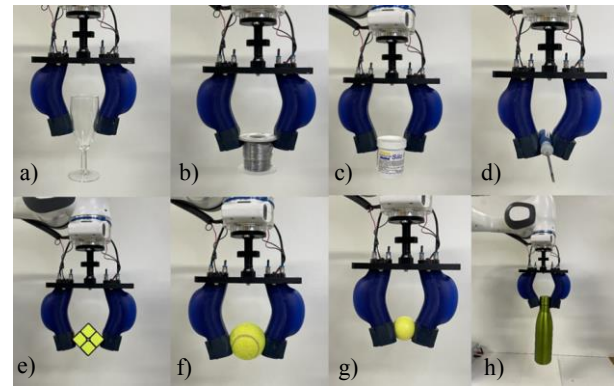


Figure 4. Examples of grasping with the variable stiffness gripper. The new gripper is able to handle objects with complex shapes that are challenging for rigid grippers or conventional soft grippers. (a) fragile glass, (b) Coil reels, (c) Cylinder box, (d) Screwdriver, (e) Rubik's cube, (f) Tennis ball, (g) Golf ball, (h) Flask

printed probe with a diameter of 5 mm is used to continuously apply forces into the center of the stiffening section at a crosshead speed of 10 mm/min. Forces and displacement data were collected using MERLIN software (INSTRON Int. Ltd., High Wycombe, United Kingdom). For each sample, the tests were run three times to ensure repeatability and the average results are shown in Fig. 3c. In the first sample with silicon, the applied force doubled when the voltage was increased from 0 to 24 V and reached 2.2 N. After mixing the MR fluid with silicon, this amount is increased by approximately 1.7 times at 24 V and reached 3.6 N. When the magnetic elastomer is placed in the third sample, the total magnetic field becomes stronger. At 24 V, the applied force reached 9 N, which is four times greater than the first sample (Silicone alone) at 24 V with a displacement of 10 mm. The results indicate that the stiffness of the sample can be easily modified using a combination of magnetic elastomer, silicone, and MR fluid.

The next experiment tests the performance of the proposed soft gripper by grasping objects that vary in shape and weight (Fig. 4a-h). As discussed in the previous section, the process of grasping an object starts by activating the SFA toward the object. When contact with the object is detected using the embedded tactile sensor, the electromagnet is activated to increase the gripper's stiffness. Additionally, the shape of the gripper is adapted to the profile of the object, resulting in stable and reliable grasping by increasing the number of contact points. In this experiment, objects with irregular and complex shapes like a stapler, glass, PCBs, coil reel, and bottle with spray nozzle (Video S2) were tested. Furthermore, the proposed gripper is also used to grasp some deformable objects such as a shoe sole, a doll, and foams (Video S3), as well as delicate and fragile glass filled with water (Video S4). The proposed gripper has been mounted on a cobot (Franka Emika) which allows to define a specific grasping strategy with similar conditions for different types of objects. According to the experimental results, the developed soft gripper can grasp all test objects with a high success rate. For each object, the test has been repeated 5 times, and the minimum success rate is 80% for the bottle, while for the other objects, it is 100%. In terms of payload, the range is from 5 g (screw) to 800 g (bottle with spray nozzle). As an additional benefit, unlike other methods like jamming,

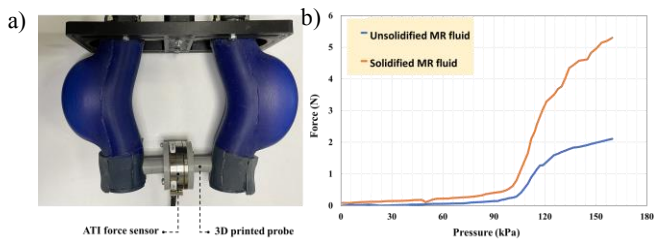


Figure 5. Produced gripping force of two soft robot fingers with corresponding applied pressure. (a) An ATI force and pressure sensors are used to measure gripping force and applied pressure. The force sensor is also utilized to calibrate the two embedded tactile sensors inside the fingers using a 10 mm diameter 3D printed probe (b) As this graph shows, the activation of the magnetic field increases the gripping force.

solidification of the MR fluid does not affect the grasping performance. The fourth experiment demonstrates the effectiveness of the proposed stiffening method. Pressure is applied to the fingers and the resultant force is measured on the grasped object. The fourth experiment demonstrates the effectiveness of the proposed stiffening method. Pressure is applied to the fingers and the resultant force is measured on the grasped object. The applied pressure is controlled using a pump with a solenoid valve and is measured using a pressure sensor (MPX520). At the stiffening section, the force is measured by the embedded tactile sensor calibrated by a precision ATI force sensor (ATI1400) as shown in Fig. 5a. The data is collected with a sample rate of 2 ms. In addition, to increase the accuracy of the data collection, this experiment is repeated three times, and the average result is shown in Fig. 5b. This figure shows the range of the gripping force produced by the two soft fingers as a function of the applied pressure with or without the solidification of the MR

Table 1. Specification of different object shapes for testing the gripper's performance

Object Shape	Cylinder	Cube	Sphere	Star
Dimension (mm)				
	$h = 25$ $R = 50$	$a = 50$	$R = 50$	$\theta = 38^\circ$ $h = 40$

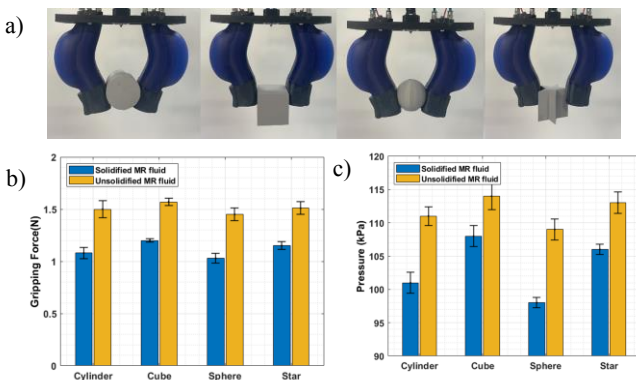


Figure 6. Evaluation of the stiffening section with objects of different shapes. All 3D-printed objects used in this experiment have the same weight of 50 g. (a) 3D printed of different object shapes (cylinder, cube, star, and sphere) for testing the gripper's performance, (b) By activating the magnetic field, the required gripping force is reduced. As a result, it is more effective when applied to spheres and cylinders. Two tactile sensors embedded in the fingertip of the finger measure the exerted force during grasping, (c) In addition, the amount of pressure required for grasping and holding has decreased.

fluid (presence of magnetic field). In the initial state (blue line), the MR fluid is in a fluid state with low stiffness, resulting in a relatively low force when pressure is applied. When the magnetic field is activated (red graph), the MR fluid solidifies, leading to higher force production with increased pressure, notably around 100 kPa for sensor gripping. The nonlinear behavior of the MR fluid enhances the applied force, particularly as the layers near the electromagnet stiffen under additional pressure. The results show that solidification of the MR fluid increases the stiffness, as the gripping force can be increased from 2.11 N to 5.3 N (2.5 times) at 160 kPa pressure. To investigate the effect of object shape on the performance of the soft gripper, different objects with and without solidifying the MR fluid were considered for grasping. The goal of this experiment is to find the minimum gripping force (holding the object). Table 1 shows four 3D-printed objects with different shapes (Cube, Sphere, Cylinder, and Star (Fig. 6a)). These objects are hollowed out and filled with small non-ferromagnetic balls to achieve a weight of 50 grams for each object. The minimum gripping force is estimated by reducing the applied pressure and corresponding gripping force of an already grasped object until the object is released from the gripper. More specifically, the procedure is as follows: 1) The solenoid valves are activated, and the soft fingers begin to bend and clamp the object; 2) The tactile sensor detects a contact point which activates the electromagnet that solidifies the MR fluid; 3) The solenoid valves are deactivated to release the pressure (opening) for a millisecond and then they close again to maintain the current pressure; 4) The force and pressure gauges are read once the gripper releases the object.

The procedure is repeated five times for each object and compared to the results obtained when MR fluid is not solidified. Fig. 6b illustrates the experimental results. It shows that the stiffening of the fingertips reduces the minimum gripping force required to achieve a stable grasp regardless of the shape of the objects. It is remarkable that the Sphere and Cylinder show a more stable grasping than the Cube and Star. This is because grasping stability improved with the increase of the contact points with the object. Fig. 6c shows that adding the stiffening section to the gripper not only increases the grasping stability, but also reduces the pressure required to grasp an object, as well as the corresponding gripping force.

The proposed soft gripper has the advantage of being able to grasp a wide range of objects without knowing the exact position or the required gripping force. To validate this, a grasping strategy to ensure the robustness of the grasping during high acceleration is tested on the four objects from the previous experiment. The gripper is attached to the Franka Emika robot and its performance is evaluated according to its ability to pick and place items quickly. The experimental procedure consists of the following steps: 1) Move the robot arm to the gripping position and grab the object; 2) Lift the object 20 cm high; 3) Hold the object for five seconds; 4) Place the object in the primary position; 5) Perform this procedure for the next object; 6- Repeat steps 1 to 5 for 20 times. To better assess the performance of the stiffening section, the same minimum pressure estimated from the previous experiment is used for gripping objects. This pressure is equal to 114, 111, 113, and 109 kPa for the cube,

cylinder, star, and sphere respectively. This process is performed for each object with and without applying the magnetic field and by varying the speed of the robot arm from 50 mm/s to 100 mm/s. The procedure is considered successful if the object does not fall during the entire procedure. In addition, the primary position of the object or the contact points may be slightly changed during regrasping. Therefore, the gripper should be able to grasp objects with these changes to demonstrate its robustness. For example, when grasping the star, the grasping points are changed every time, but the proposed gripper can still hold the object with a high success rate. In Table 2 and Video S5., the success rate of the proposed gripper is compared with and without solidification of the MR fluid. The results show that changing the stiffness improves the success rate when grasping objects with various shapes. Furthermore, the proposed gripper performs better when an object has curves or edges. For example, it can grasp the sphere and cylinder with a 100% success rate. Although the proposed fingers can grasp the cube with a success rate of 85%, it is still higher than grasping it without stiffening, which is about 65%.

Table 2. Grasp success rate

Speed and acceleration	50 mm/s speed with an acceleration of 10 mm/s ²		100 mm/s speed with an acceleration of 20 mm/s ²	
	MR fluid	Solidified MR fluid	MR fluid	Solidified MR fluid
Cube	65%	85%	55%	80%
Cylinder	70%	100%	65%	100%
Sphere	75%	100%	60%	100%
Star	65%	95%	60%	95%

IV. CONCLUSION

A novel soft gripper with variable stiffness, designed for robust grasping, has been presented. The gripper comprises two sections: a pneumatic chamber functioning as an actuator, and a stiffening section responsible for controlling the stiffness and shape of the fingertip based on the object's shape. The stiffness can be easily controlled by solidifying the MR fluid with a response time of a few milliseconds. The design of the gripper not only allows it to grasp a wide range of objects with different shapes but also increases the contact points between the gripper and the object ensuring a reliable and secure grasping. The soft finger is made from silicon liquids with 3D-printed manufactured molds. A simple fabrication procedure has been described to build soft fingers easily and quickly. An electromagnet combined with a magnetic elastomer and a permanent magnet provides an adequate magnetic field to solidify the MR fluid. With the proposed design, the electromagnet size is reduced, and the current is kept low. This allows the gripper to be utilized more easily than previous grippers based on MR fluid methods [39]-[31] that require large electromagnets and high currents. A tactile sensor has been embedded within each finger to measure the applied force and to detect the contact point. This allows triggering the magnetic field, to solidify the MR fluid and consequently vary the stiffness of the fingers. Different experiments have been performed to assess the performance of the proposed soft gripper. The stiffening section of the proposed gripper has been analyzed with

respect to the produced force. The results indicate that solidifying the MR fluid increases the gripping force by 2.5 times, reducing the minimum force needed to achieve a stable grasp regardless of the object's shape. Additionally, it reduces the force required to grasp an object. Table 3 compares the proposed gripper's performance with previous approaches in the literature based on some essential qualitative evaluation in terms of stiffness and de-stiffness speed, easy fabrication workspace and scalability. Compared with the previous solutions, our hybrid gripper consists of low-cost materials that improves its performance concerning the range of stiffness variation, shape adaptability, operational range of workspace, high force generation, and large stroke bending.

Table 3. Comparison of single stiffening methods in soft robot applications

Stiffening Technology	Stiffness speed	De-stiffness speed	Easy Fabrication	Work space	Scalability	Ref.
DAE+ LMPA	--	--	-	-	-	[40]
Tendons + Fluidics	++	+	+	+++	-	[41]
LMPA+ Fluids	--	--	-	++	+	[42]
Granular Jamming+ Fluids	++	++	+	++	--	[43]
Layer Jamming + Fluids	++	++	-	++	--	[44]
SMP+SMA	--	--	---	++	+	[45]
SMA + Fluids	-	-	+	++	+	[46]
SMP + Fluids	-	-	+	++	+	[47]
Proposed method (MR fluid + Fluids)	++	++	+	+++	+	

In future work, we will downsize the dimensions of the gripper by building a soft electromagnet using metal liquid. Furthermore, the performance of the gripper in grasping ferromagnetic objects and its interaction with magnetic fields will be investigated.

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V. REFERENCES

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