# Employing Magnets to Improve the Force Exertion Capabilities of Adaptive Robot Hands in Precision Grasps

Lucas Gerez, Geng Gao, and Minas Liarokapis

***Abstract*— Adaptive, underactuated and compliant robot hands have received an increased interest over the last decade. Possible applications of these systems range from the development of simple grippers for industrial automation to the creation of anthropomorphic devices that can be used as prosthetic hands. These hands are particularly capable of extracting stable grasps even under significant object pose or other environmental uncertainties, due to the underactuation and the structural compliance of their designs. Despite the increased interest and the promising performance, adaptive hands suffer from several disadvantages and drawbacks. For example, the use of underactuation can lead to a post-contact reconfiguration of the fingers that compromises the force exertion capabilities of the system during pinch grasping. In this paper, we focus on the design, modelling, development, and evaluation of an adaptive robot gripper that uses magnets to adjust the reconfiguration profile of the fingers. The effect of the magnets increases the gripper's force exertion capabilities in pinch grasps, without compromising the full / caging grasps. The efficiency of the proposed gripper is experimentally validated through two different tests: i) a contact force test that compares the results of a theoretical model with the actual experimental results and ii) a grasping test that assesses the force exertion capabilities and the reconfiguration behaviour of the adaptive fingers for different implementations of the magnetic joints.**

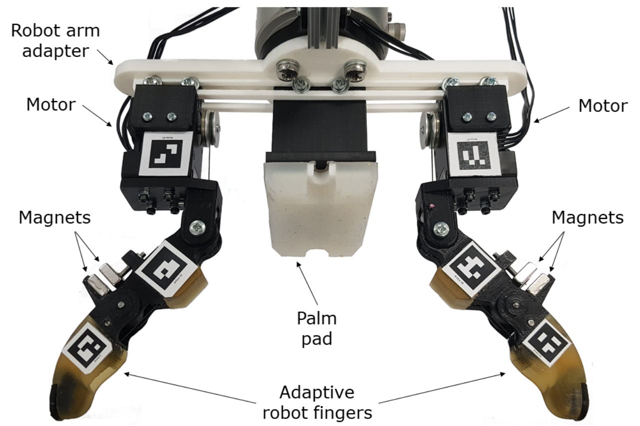


Fig. 1. The proposed design uses magnets to adjust the reconfiguration profile of adaptive hands, increasing the contact force of pinch grasps while retaining the efficiency of the full / caging grasps. The gripper consists of two adaptive robot fingers, two motors, a compliant palm pad, and a base that connects to a robot arm. The compliant palm pad provides support for the gripper to maximize its efficiency in full grasps. Each finger has two spring loaded pin joints and one flexure joint as well as magnets at the PIP joint. These magnets are used for the adjustment of the reconfiguration profile and for the force augmentation.

## I. Introduction

Over the last years, adaptive robot hands have become a popular solution for executing object grasping and dexterous manipulation due to their ability to extract stable grasps even under object pose uncertainties, their low complexity, robustness, and affordability. These hands are able to replace complex, heavy and expensive robot devices that require sophisticated sensing and complicated control laws [1], [2]. Their efficiency is due to the structural compliance and the underactuation that allow them to adjust their grasping postures according to the object geometry, maximizing the area of contact with the object [3], [4].

Despite the promising performance and their benefits, adaptive hands have also certain deficiencies and limitations. An underactuated design is characterized by a significant post-contact reconfiguration of the hand object system that imposes a parasitic object motion. This reconfiguration occurs until the system reaches an equilibrium configuration [5] and it may compromise the pinch grasping capabilities of the system. This is why adaptive hands are typically used for full / power grasps and they are not particularly efficient in the execution of fingertip, pinch grasps. During a pinch grasp, a significant amount of motor load is wasted on reconfiguration. This reduces the available fingertip force that could be applied to the object, compromising the overall grasp efficiency [6].

There are different methods available in order to avoid the post-contact reconfiguration of adaptive, underactuated and compliant robot hands. One of them is to optimize the structure of the adaptive fingers so as to stop the reconfiguration in certain finger poses and exert significantly high contact forces. Many authors have discussed this idea and how to achieve grasp stability in pinch / precision grasps with underactuated fingers [7]–[9]. Although with such an approach we guarantee the execution of stable pinch grasps, power grasps are affected and the maximum amount of force that can be exerted by the gripper is reduced [10]. An alternative solution for reducing the post-contact reconfiguration of adaptive hands is to increase the stiffness of the joints. For stiffer joints, significantly higher contact forces can be exerted before the post-contact reconfiguration of the gripper starts. The drawback of this second solution is that it leads to the development of grasping mechanisms that require more power (motor load) to execute other types of grasps (e.g., power grasp, lateral grasp, etc). Thus, there is a tradeoff between precision and power grasping efficiency.

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In this paper, we focus on the design, modelling, development, and evaluation of an adaptive robot gripper that uses magnets to adjust the post-contact reconfiguration of the fingers and to increase the fingertip forces in pinch grasps (Fig. 1). This solution does not compromise the force exertion capability of the device in other types of grasps (e.g., power grasp). When the magnetic force diminishes (the hand moves from a pinch to a full grasp), the force required to bend the default spring is significantly lower than the force required to bend a stiffer spring that would provide the same pinch grasping behavior (as the magnetic joint). This simple and low-cost solution can also be used in other adaptive grippers or hands (e.g., soft robot hands, anthropomorphic devices) without affecting the main design choices.

In order to describe the behavior of the proposed gripper we have developed a mathematical model. The accuracy of the model is validated through extensive comparisons with actual experimental results. An analysis of the finger forces and the post-contact finger motion profiles while grasping different objects has been conducted. Regarding the efficiency of the gripper, it has been demonstrated through a series of experiments involving grasping of a range of everyday life objects.

The rest of the paper is organized as follows: Section II presents the design and the modelling of the gripper, Section III details the experimental setup used for the tests and presents the experimental results, while Section IV concludes the paper and discusses some possible future directions.

## II. Design and Modelling

### A. Finger Design

The proposed robotic gripper has two fingers that are based on the fingers of the New Dexterity robot hand [11]. Each finger has two joints, the Metacarpophalangeal (MCP) joint and the Proximal Interphalangeal (PIP) joint and three main parts: a finger base, a proximal phalanx, and a third part that combines the middle and distal phalanges. The finger structure was manufactured out of PLA plastic and a polyurethane elastomer (urethane rubber Smooth On PMC-780). The elastomer is used in the middle phalanx to increase the friction between the finger and the object during object manipulation while the elastomer between the two phalanges acts like the distal interphalangeal joint (DIP). These anthropomorphic robotic fingers emulating the human index finger were designed with a tendon driven actuation scheme seen in many adaptive and underactuated grippers [12]–[15]. This is to investigate the pinch force capabilities of tendon driven underactuated fingers in everyday tasks.

Each finger has two magnets attached to the back of the proximal interphalangeal joint (PIP), one in the middle phalanx and the other in the proximal phalanx, as shown in Fig. 2. A screw connecting one magnet to the proximal phalanx enable us to change the distance between the magnets and, as a consequence, the required force to trigger the reconfiguration between the two phalanges connected. The attraction forces between magnets have an exponential relation to the distance between them, so when the PIP joint bends and the magnets move some millimeters apart from each other, the force acting against the motion decreases drastically and the magnets have no more practical effect. When this happens, the finger starts behaving as a standard robot finger with torsion springs at the joints that can be significantly weaker. For this reason, the grasps that require bending of the PIP joint, such as full grasps, are not affected by the proposed solution. In order to analyze the advantages of applying magnets at the PIP joint, a mathematical model of the finger was developed to estimate the maximum force that could be exerted with the distal phalanx.

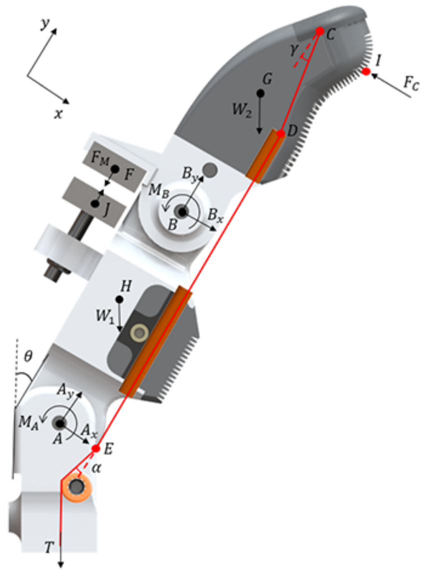



Fig. 2. A robot finger model. The red line represents the tendon that is anchored at the fingertip (point $C$) and rerouted at points $D$ and $E$. The routing tubes and the bearing that change the tendon direction are highlighted in orange. The magnets' centers of gravity are located at points $F$ and $J$. $A$ and $B$ are the positions of the pin joints, and $G$ and $H$, the centers of gravity of each phalanx. $I$ is the point where the contact force ($F_c$) is applied. A mathematical model was developed to assess the benefits of the addition of the magnets at the PIP joint.

### B. Contact Force Estimation

Fig. 2 shows the proposed model for the index finger. $A$ and $B$ are the MCP and PIP joints, respectively. $A_x$, $A_y$, $B_x$, and $B_y$ are the reaction forces at the pin joints in $x$ and $y$ directions, while $M_a$ and $M_b$ are the moments generated by the torsion springs that are located at joints $A$ and $B$. The red lines depicted represent the tendon routing on the finger. The tendon is anchored at the fingertip, $C$, and goes through channels inside the phalanges. The tendon routing changes direction at points $D$ and $E$, generating the angles $\gamma$ and $\alpha$ and being pulled with a force $T$. The magnets attract each other with a force $F_M$, centered at points $F$ and $J$. $G$ and $H$ are the Center of Gravity (CoG) of the middle and the part combining the middle and distal phalanges, respectively, and $W_1$ and $W_2$ are their weights. $\theta$ is the bending angle of the finger (in Fig 2, $\theta = 30°$). The model aims to calculate the maximum contact force, $F_C$, that can be applied to $I$, perpendicularly to the finger direction, $y$. Since the force is applied directly to the fingertip and the polyurethane elastomer structure does not show high deformations during pinch grasping, the elastomer structure was considered rigid for this model. The friction between the tendon and the finger structure was neglected due the small rerouting angles, the smooth surface and the low friction of UHMWPE (Ultra-High Molecular Weight Polyethylene) fibers [16].

The situation of maximum contact force will happen on a static condition right before the magnets move apart from each other. For this static condition the sum of moments generated by all the forces at point $A$ should be zero, as shown in Eq. 1, considering only the middle phalanx of this finger.

$$\begin{aligned}\sum M_A = 0 = M_a - M_b + B_x\overline{AB_y} - F_M\overline{AF_x} - T\sin(\alpha)\overline{AE_y} \\ +T(1-\cos(\alpha))\overline{AE_x} - W_1\sin(\theta)\overline{AG_y} + W_1\cos(\theta)\overline{AG_x}\end{aligned} \tag{1}$$

Considering only the part composed of the distal and middle phalanges, the sum of moments generated by all the forces at point $B$ should be zero, as shown in Eq. 3 and the sum of forces at point $B$ in the $x$ direction should also be zero, as shown in Eq. 2.

$$\sum F_x = 0 = B_x - F_c + W_2\sin(\theta) \tag{2}$$

$$\begin{aligned}\sum M_B = 0 = M_b + F_C\overline{BI_y} + F_M\overline{FB_x} - T\sin(\gamma)\overline{BC_y} - \\ T\cos(\gamma)\overline{BC_x} + T\sin(\gamma)\overline{BD_y} - T(1-\cos(\gamma))\overline{BD_x} - \\ W_2\cos(\theta)\overline{BH_x} - W_2\sin(\theta)\overline{BH_y}\end{aligned} \tag{3}$$

Using these equations, it is possible to isolate the tension $T$ from Eq. 1 and 3 to have only one equation to find $F_C$ in terms of $F_M$, the angles, the moments generated by the torsion springs and the aforementioned distances.

## III. Experiments and Results

The experiments that assessed the performance of the magnetic joint and the gripper were divided into two parts. The first part focused on comparing the values of contact force obtained through the model with experiments measuring the contact force in different angles, while the second part involved grasping different objects comparing the fingertip forces and the joint angles for three specific distances between the magnets. Full grasp experiments were also conducted to verify the effect of the magnetic joint when full closure of the finger is required.

### A. Contact Force Measurement

The contact force experiment consisted of measuring the contact force of a robotic finger in different conditions applying the proposed magnetic solution varying the distance between the magnets before each measurement. The goal of this experiment was to verify if the addition of magnets at the PIP joint can increase the contact force of the finger but also compare the results with the proposed model in order to be able to optimize the finger design to achieve better results in terms of motion and forces.

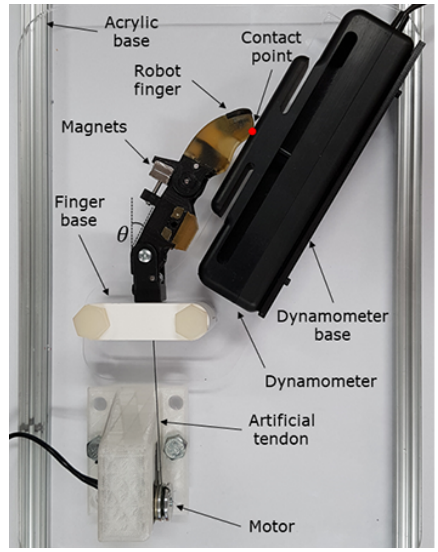



Fig. 3. The experimental setup used for the contact force experiments. The contact force was measured to assess how the existence of magnets at the PIP joint affects the post-contact reconfiguration of the hand as well as to provide experimental results for comparison with the results of the mathematical model developed. A dynamometer was used to measure the contact force applied by the finger. This experiment was conducted for four different finger angles ($\theta$): 0°, 30°, 60°, and 90°. The motor, the finger and the dynamometer were connected to bases that were fixed to an acrylic plate. The test was executed four times (trials) for each distance between the magnets (6 distances + the "inf" case) for all the examined angles (4 angles).

For this first experiment, the setup shown at Fig. 3 was used. This setup was composed of an index robot finger connected to a base that was attached to an acrylic plate. An artificial tendon connected the finger to a Dynamixel XM430-W350-R motor that was also connected to the acrylic base through a case. A Biopac MP36 dynamometer (Biopac Systems, Inc., Goleta, California) was used to measure the fingertip forces exerted in each situation. The dynamometer was fixed to the acrylic base in different angles from the finger (0°, 30°, 60° and 90°) using a plastic mount. The device was positioned to obtain perpendicular contact forces. The magnets on the finger were placed in seven different distances from each other, from 0 mm (direct contact between the magnets) to 5mm, plus the condition without the magnets. The experiment was executed four times for each angle and for each distance between the magnets. The force considered was the maximum value obtained before any motion between the proximal and middle phalanges, that is the same calculated force from the proposed model. Fig. 4 shows the comparison results of the proposed model and the experiments.

Analyzing model and experiment results, it is possible to observe that the addition of magnets to the PIP joint increases up to six times the fingertip force that can be achieved, depending on the distance between the magnets. Comparing the data from the model and the experiments, we notice that the model developed presents similar results to the experiments. For distances between the magnets from 1 mm to 5 mm, the forces from the model and the experiments are

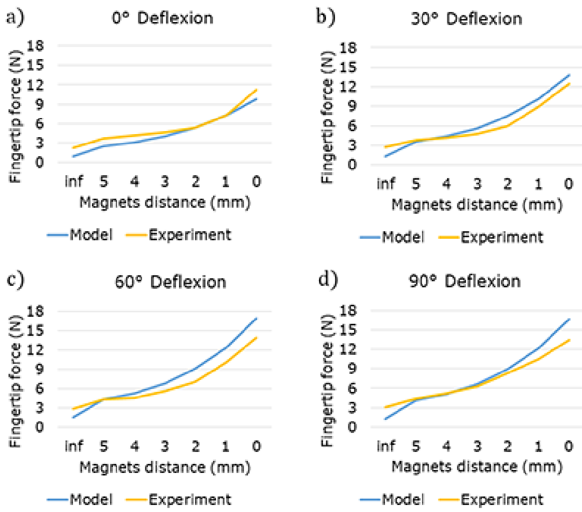



Fig. 4. The graphs compare the results obtained from the mathematical model (blue) and the experiments conducted (yellow) for four different finger angles, ($\theta$) (see Fig. 3), 0°, 30°, 60° and 90°, and six different distances between the magnets, varying from 0 mm (magnets in contact with each other) to 5 mm. We consider also the reconfiguration without the magnets (labeled as "inf" in the graphs to denote an equivalence to an infinite distance between the magnets). The model and the experiments display similar patterns in all the angles analyzed. According to the experiments, the addition of magnets at the PIP joint can increase more than four times the fingertip force that can be achieved.

similar, for all angles tested. Comparing both the extreme conditions, without the magnets (Inf) and when they are touching each other (0 mm distance), the results show higher differences between the model and the experiments if compared to the interval from 1 mm to 5 mm. The model underestimates the value for the condition without the magnets because it doesn't take into account the friction at the joints. This friction value is the same in all other experimental conditions, however, it represents a much smaller percentage of the overall value. The model and the experiments show discrepancies for the condition where magnets touching each other due to the exponential behavior of the attractive forces on the magnets. A small difference on the magnetic force calculation can generate high discrepancies on the proposed model. Since we have obtained similar results between the model and the experiments, this model can be used in the future in a closed loop control scheme to predict contact forces and optimize the grasping and manipulation of objects.

### *B. Pinch Grasp Analysis*

The second experiment consisted of an analysis of the gripper motion while grasping different objects. This experiment also measured the fingertip forces to assess the advantage of the joint with the magnets attached while grasping everyday life objects.

The experimental setup used for this experiment is shown in Fig. 5. The proposed gripper and an HD camera were mounted to a robot arm (UR5, Universal Robots, Odense, Denmark). Two force sensors (CS8-100N, SingleTact, Los Angeles, CA, USA) were connected to the fingertips of the gripper to measure the contact forces through a microcon-

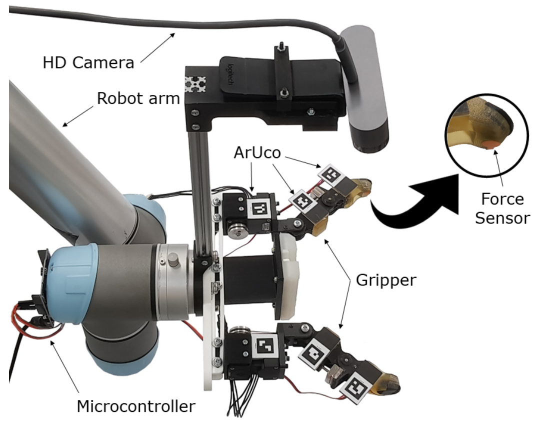



Fig. 5. A robot arm, an HD camera, force sensors and the proposed gripper were used in the second experiment. The gripper and the camera were mounted at the end-effector of the robot arm allowing the camera to track the ArUco markers so as to capture the joint angles during object handling. Force sensors were fixed at the fingertips of the gripper (highlighted in the figure) to measure the contact forces and perform contact detection. A dedicated microcontroller was used for data collection purposes.

Fig. 6. Eight objects from the YCB object set [17] were used for the execution of the pinch grasping and full grasping experiments.

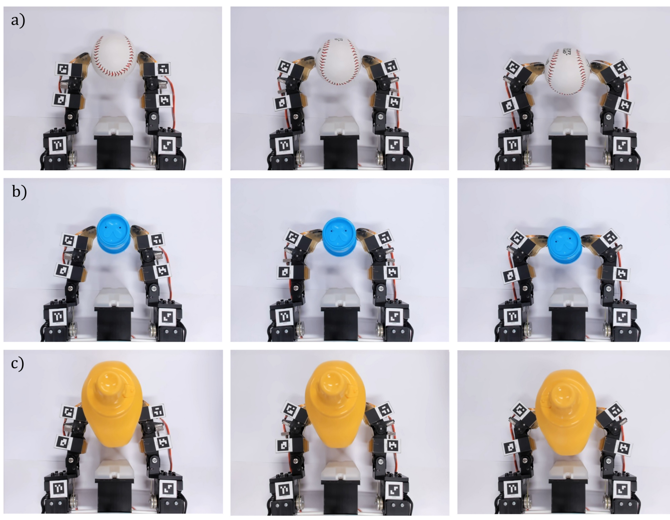
troller. The camera was used to track six ArUco markers to measure the joint angles while grasping different objects. The pinch grasp was executed until post-contact reconfiguration was observed. All eight daily life objects (Fig. 6) used in this experiment were selected from the YCB object set [17], an object set designed for facilitating benchmarking in robotic manipulation and grasping.

Three examples of objects grasped and the behavior in each condition can be seen in Fig. 7 from the HD camera's top view perspective. Table I shows the average of maximum fingertip forces for three conditions tested: without the magnets, 2 mm distance between the magnets, and the magnets touching each other (0 mm). The experiment was executed five times to all eight objects in each of the three described conditions. The effect of the magnetic joint can be easily noticed analyzing the images and the data from the table. For instance, for object shown in Fig. 7-a), a baseball ball, the maximum fingertip forces on the condition that the magnets are touching each other (10.25 N) is more than three times higher than the one when there is no magnetic interference

TABLE I

AVERAGE OF MAXIMUM FINGERTIP FORCES (BEFORE RECONFIGURATION) OBTAINED FROM THE PINCH GRASP EXPERIMENT FOR FIVE TRIALS. THE OBJECTS USED WERE: A) A BASEBALL BALL, B) A PEAR, C) AN APPLE, D) A MUSTARD BOTTLE, E) A CAN, F) A YELLOW BUCKET, G) A BLUE BUCKET, H) A JELLY BOX.

| Test Case | Fingertip Force per Object (N) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | a) | b) | c) | d) | e) | f) | g) | h) |
| 0 mm | 10.24 | 11.10 | 10.71 | 10.98 | 11.30 | 12.21 | 9.45 | 7.52 |
| 2 mm | 6.09 | 6.48 | 5.86 | 4.39 | 6.32 | 5.15 | 6.59 | 4.39 |
| No magnet | 2.66 | 2.58 | 2.61 | 2.62 | 3.43 | 2.40 | 2.26 | 2.57 |




0 mm 2 mm No magnets

Fig. 7. The experiment compared the fingertip forces and the finger configuration while grasping eight different objects in three different test scenarios of the magnetic joint: without the magnets, with a 2 mm distance between the magnets, and with the magnets touching each other (0 mm distance). The figure shows the gripper configuration while grasping a baseball ball (subfigure a), a small bucket (subfigure b), and a mustard bottle (subfigure c). The results show that the existence of magnets leads to stable grasps of the objects with less reconfiguration and better force exertion capabilities.

(2.66 N), and many other objects presented an average of maximum fingertip forces higher than 11 N. The required pinch force in order to manipulate most of the objects that are encountered during daily living is less than 10.5 N [18], so the proposed gripper is capable of grasping most of the objects encountered in daily living.

Fig. 8, reports the fingertip forces according to the joint angle variations in the three conditions tested for the baseball ball. While approaching the object, the MCP joint angle increases until touching the object with the fingertip.

Post-contact, the finger stays static, pressing the object and keeping the joint angles the same while the fingertip forces increase. The maximum fingertip force is reached right before the beginning of post-contact reconfiguration (highlighted in the graphs). When reconfiguration between the two phalanges is observed, the force drastically decreases, increasing the PIP joint angle. When the PIP joint angle changes, the proximal phalanx goes backwards, decreasing the MCP angle. This drop in force is more easily noticed when the magnets are used, however, even without the magnets it is still possible to verify that post-contact reconfiguration reduces the fingertip forces.

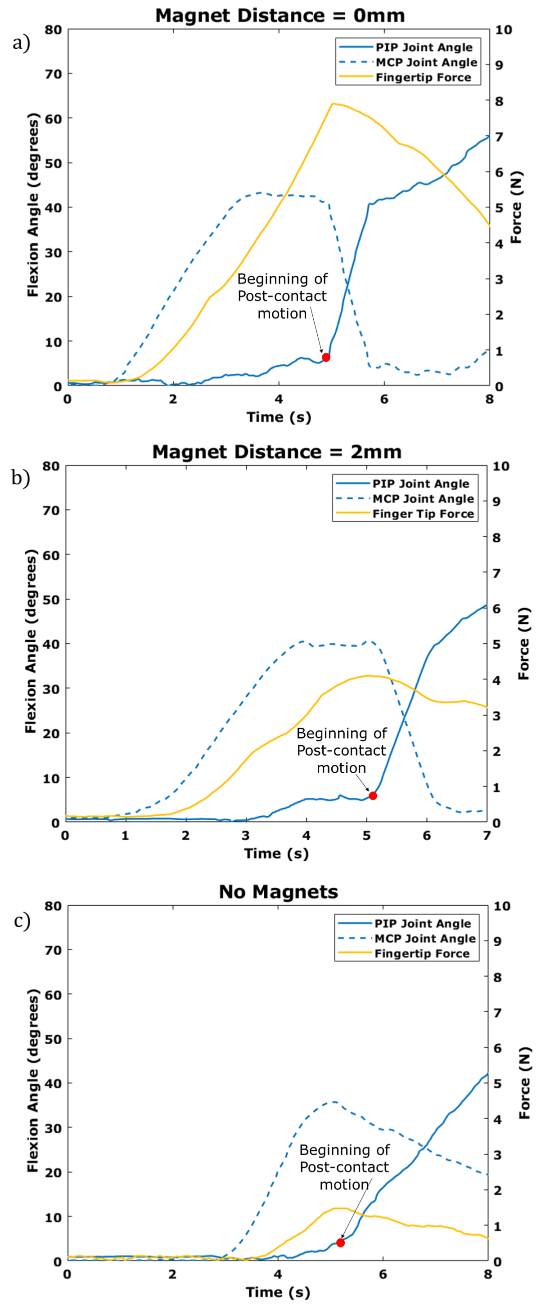



Fig. 8. Results obtained from the grasping experiments for a baseball ball. The graphs show the variation of the MCP joint angle, the variation of the PIP joint angle, and the variation of the fingertip forces while grasping the object for three different test scenarios: a) with the magnets touching each other (0 mm), b) with a 2 mm distance between the magnets, and c) without the magnets. We also highlighted the moment when the post-contact motion (reconfiguration) starts. When the post-contact reconfiguration starts, the PIP joint angle increases quickly, while the proximal phalanx goes backwards decreasing the MCP joint angle. At the same time, a significant force reduction is observed. The maximum fingertip force values are reached before the start of the reconfiguration of the finger, for the test case where the magnets touch each other (0 mm distance).

TABLE II

AVERAGE OF MAXIMUM FULL GRASP FORCES EXERTED BY THE GRIPPER ON THE JELLY BOX. DURING THIS EXPERIMENT WE CAPTURED THE FULL GRASP FORCES AND THE MOTOR TORQUES AT THE END OF THE GRASPING MOTION (WITH THE GRIPPER FULLY CONFORMED TO THE OBJECT GEOMETRY) FOR DIFFERENT MAGNET POSITIONS.

| Output Measures | Test Case | | |
|---|---|---|---|
| | 0mm | 2mm | inf |
| Grasp Force (N) | 23.24 | 22.49 | 22.73 |
| Right Motor Torque (Nm) | 0.66 | 0.66 | 0.65 |
| Left Motor Torque (Nm) | 0.92 | 0.94 | 0.93 |

### C. Full Grasp Analysis

Full grasp experiments were also conducted to verify if the proposed solution could affect the efficiency in this type of grasp. The same setup from the previous experiment was used (Fig. 5) with the addition of three force sensors at the proximal phalanges and palm pad to verify if the total contact force would vary with differing magnet positions. An object that ensured all the sensors were in perpendicular contact with the object surface during a full grasp was selected from the object set (jelly box). Table II, shows the results for the full grasp experiment. The grasp force was considered as the sum of all the forces applied to the five force sensors. No significant difference in total contact force on the object and torque exerted by the motors was observed, validating the initial assumption that after the PIP joint bends significantly, the magnets do not affect the motion of the finger anymore and the fingers with and without the magnets behave similarly for full grasps.

Thus, the experiments with the proposed robotic gripper show that the fingertip forces while grasping different objects can be increased more than four times with the addition of magnets, if compared to the same gripper without the magnets, due to the delay of finger reconfiguration. This range of applicable fingertip forces, above 12 N, is enough to be able to grasp and handle most daily life objects that require a pinch or similar grasp. Although the proposed solution can increase the fingertip forces, it also has some limitations. The delay in the reconfiguration of the finger results in a delay to execute grasps that require full closure of the finger, like full grasps and lateral grasps in robot hands. This behaviour can be undesired in situations that quick movements are necessary.

## IV. CONCLUSION

In this paper, we proposed an adaptive, underactuated and compliant robot gripper that uses magnets to adjust the post-contact, reconfiguration profiles of the fingers, increasing the force exertion capabilities of pinch grasps without sacrificing the efficiency of full grasps. The proposed gripper uses magnets on the spring loaded pin joints that delay the post-contact reconfiguration of the system. The concept was modelled and the results of the theoretical analysis were compared to the actual experimental data. The results demonstrate that the proposed robotic gripper can generate higher contact forces for pinch grasps without interfering with the full grasping capabilities of the hand. The amount of pinch force achieved during the grasping experiments shows that the proposed gripper can exert the required pinch force to execute successfully a wide range of everyday life tasks.

Regarding future directions, we plan to miniaturize the proposed solution and to investigate other mechanisms that can improve the force exertion capabilities of adaptive robot grippers and hands in precision, pinch grasps.

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