2026 IEEE International Conference on Robotics and Automation (ICRA 2026)
June 1-5, 2026. Vienna, Austria

Soft Vortex Gripper for Dexterous Manipulation using Hand-Like Robots

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Abstract— **Dexterous manipulation remains a constant challenge in robotics, particularly in achieving precise in-hand manipulation, force modulation, and spatial positioning. There have been many attempts at solving these issues, with varying degrees of success. These attempts include friction-enhancing surfaces, gecko-inspired adhesives, electrostatic grippers, and suction-based mechanisms which are limited by surface dependency and inadequate adaptability. We propose integrating a soft vortex gripper with rigid nozzles into the fingertips of a hand-like robotic manipulator. This design combines the malleability of soft silicone materials for delicate grasping tasks with the strength of rigid components to maintain consistent vortex formation under pressure load. The integrated gripper enhances surface friction, enables adhesion to irregular geometries, and provides more precise pressure control. We programmed and mounted the soft vortex gripper onto the fingertip of a robotic hand, which was then installed on a Roboligent OPTIMO 7-DOF robotic arm. We tested square, tapered, and rounded gripping surfaces and found that the square-faced design achieved the highest gripping force of 0.59N at 300 kPa, outperforming others by over 31%. Using the hand-like robotic arm, we tested the embedded soft vortex gripper by extracting Jenga blocks from a fully constructed tower without pre-loosening, and pulling individual playing cards from a deck. The gripper consistently succeeded in removing singular playing cards and was able to both push and pull Jenga blocks from the tower with control and precision. The experimental results support its potential as a tool for enhancing robotic dexterity, delivering consistent results across diverse manipulation tasks.**

I. INTRODUCTION

The current state-of-the-art in robotics includes the design of highly dexterous kinematically bioinspired robotic hands and grippers [1]–[3]. However, much research effort still focuses on increasing finger forces, improving in-hand manipulation, and refining both force control and spatial positioning to better mimic human hands and tactile sensing abilities [4], [5]. Novel finger designs focus on integration of adhesive, friction, or lifting elements for more dexterous fingers. Recent studies show that the human finger tip microstructure, together with skin secretion, creates adhesion between the fingers and the contacted object [6], [7]. This, in turn, leads to an increase in holding force and improves the efficiency of dexterous grasping and manipulation [8]. In addition to natural skin secretions, humans often use other fluids and adhesives to improve their dexterous performance such as licking a finger or using a finger wetting pad or moistener cream to help during high volume document handling tasks (Fig. 1-Top).

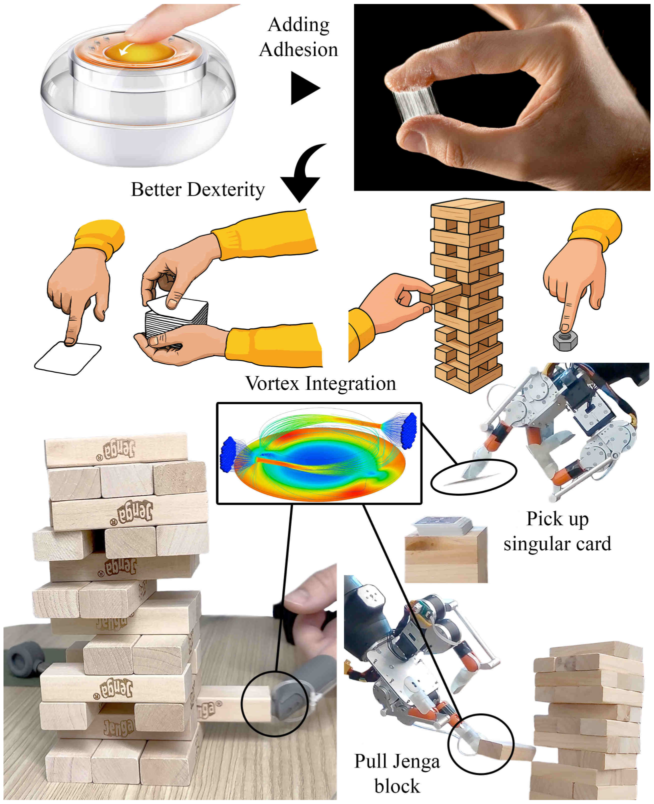

Fig. 1: Top - Natural skin moisture and additional adhesives can increase the interaction force between the human finger and an object lead to better dexterity in for grasping and manipulation tasks (e.g., document sorting); Bottom - Our addition of a soft vortex gripper on the fingertip of a robotic hand enables more dexterous manipulation of single playing cards and removing a single block from a tower.

Unlike human fingers, robotic grippers enable the integration of various subsystems that could provide fingertip capabilities that are not possible for humans, potentially compensating for the lack of a dynamic skin. The beneficial capabilities of these additional subsystems include: increasing frictional properties due to certain materials and microstructure [12]–[15]; adhesive properties due to gecko-inspired surfaces [16], [17]; adhesion due to electrostatic effects [18], [19]; adhesion due to additional friction form

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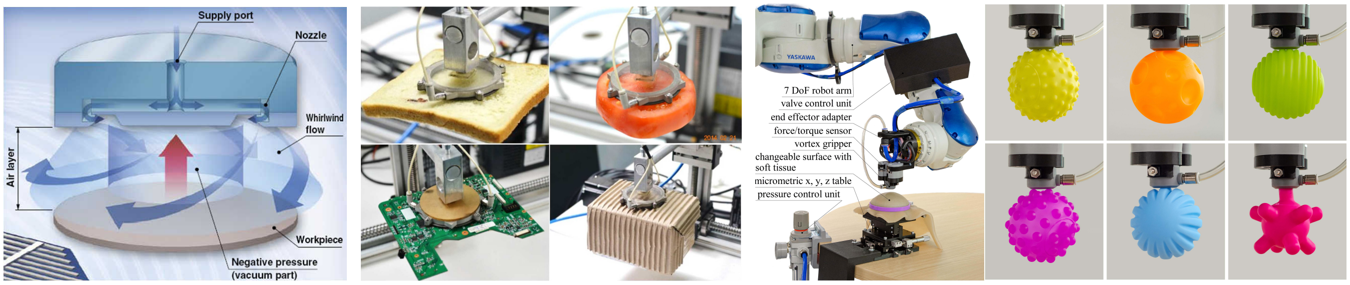


(a) (b) (c)

Fig. 2: Vortex grippers, which are a type of jet gripper devices: (a) compressed air direction that form a vortex flow that creates a lifting effect in the center of the gripper [9]; (b) application of vortex technology for grasping objects in manufacturing and assembly (electronics, food, packaging, etc.) [10]; (c) novel vortex gripper for grasping soft tissue of various shapes [11].

by shape memory polymer [20], [21]; tunable adhesion due to active changes in material parameters [22]; lifting due to a vacuum source [23], [24]; and combinations of effects [25], [26]. When implemented in robotic fingertips, these capabilities can facilitate grasping through easier control strategies and more robust interaction with the object.

However, these enhanced capabilities can be difficult to implement in real conditions, as they have their advantages and disadvantages. For example, increasing the frictional properties using additive materials does not allow objects to be attached to the fingertip, unlike gecko-inspired surfaces. On the other hand, gecko-inspired surfaces do not work well with rough objects, which are better grasped using electrostatics. Unfortunately, the electrostatic method requires laboratory-like environmental conditions, and when dust in the air and humidity changes, they can lose effectiveness. Increasing the frictional properties using shape memory polymer is sensitive to surface roughness and geometry, so it has limitations, although it is very effective in combination with other methods. Vacuum suction cups also provide great grasping capabilities, but they lose their effectiveness when depressurized due to porosity, roughness, and the complex shape of the object. Overall, there is a fundamental challenge in developing more versatile capabilities to be implemented within robotic fingertip to provide better dexterity, while ensuring delicate interaction and sufficient lifting force while maintaining an appropriate footprint to be realistic.

In this paper, we propose the development of a dexterous fingertip gripper leveraging the vortex effect (Fig. 1-Bottom), resulting in a design which provides a delicacy of interaction with the object due to the construction of the vortex chamber from a soft material, as well as a unique ability to lift objects using ejected air, which does not require prior physical contact with the object. To our knowledge, this is the first paper that presents the design, fabrication, and testing of a soft vortex gripper that combines a soft body with rigid nozzle elements. Furthermore, we evaluated various surface parameters of the integrated soft vortex gripper (i.e., square, taper, and round) through experimental studies at different supply pressures. Finally, we demonstrate the versatility of our novel fingertip gripper through dexterous grasping and manipulation of objects such as playing cards and blocks (e.g., Jenga), using a 7-DOF robotic arm.

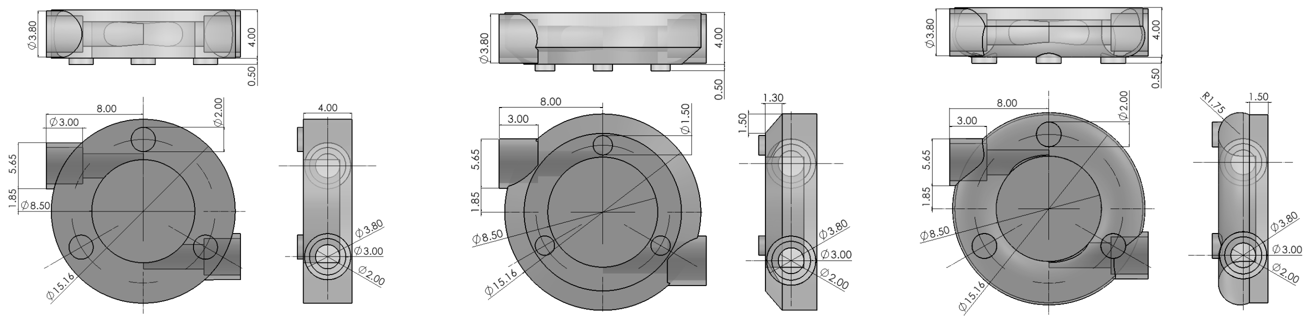
II. BACKGROUND

There are a large number of robotic grippers with soft fingers [27]–[36], which aim to increase dexterity, flexibility, and adaptability during gripping and manipulation. All of them solve the problem of adhesion and lifting of objects to the fingers in different ways. The most effective and versatile method is the integration of classical or bio-inspired suction cups into the fingers [37]–[40]. This allows for ensuring sufficient accuracy due to the forward and inverse kinematics of rigid fingers. At the same time, thanks to the soft elements of the suction cup, it is possible to somewhat adapt to the contours of the object. However, suction cups do not work well with many common objects including films, textiles, paper, wood, etc., which often requires additional lifting force at the fingertips. Therefore, we focused our design efforts on adapting on jet-type grippers [9], which have significant advantages specifically for the delicate types of objects described above.

There are four major types of jet grippers: those with a developed active surface (Bernoulli with cylindrical nozzles), ejection (Bernoulli ejection), vortex (Fig. 2), and supporting (multi-nozzle forming a pneumatic cushion) grippers. Among them, only Bernoulli and vortex grippers can be integrated into a fingertip due to inherent design features. Bernoulli grippers have higher lifting force and mass flow rates compared to vortex grippers [9], [41], making them the best choice for flat [42], porous [43], fragile [44], and deformable objects [45]–[48].

However, in our case, we aim to achieve greater versatility of surfaces with which the fingertip can interact by making the gripper from a soft material, and the ability to grasp various surfaces (Bernoulli grippers have problems with this). For this purpose, the idea of using a jet vortex gripper was proposed (Fig. 2a), the principle of which is to eject compressed air through tangentially placed nozzles into a cylindrical cavity, which leads to the rotation of air flow with increasing speed and exits through the radial gap between the object and the active surface of the gripper. Since air rotates, centrifugal force acts on the air flow, and a negative pressure is formed in the central zone of the gripper. This leads to the lifting of the object to the gripper's friction elements.

Due to the low flow rate of compressed air and the insignificant influence of the shape and rigidity of the object



(a) Square Gripper Dimensions (b) Tapered Gripper Dimensions (c) Round Gripper Dimensions

Fig. 3: Dimensions of all three gripper designs including round (a), tapered (b), square (c). Highlighting differences in the contact surface geometry as well as the friction element placement and dimension.

on the gripper's force characteristics, this technology has found significant application in manufacturing (Fig. 2b). The main areas of application include electronic devices [10], [49] (circuits, silicon chips, electrical components, etc.), where there are many small elements on the surface, which make it impossible to use vacuum suction cups (due to loss of vacuum) and finger grippers (due to the fragility of the circuits). We can also often find the implementation of this technology in food factories to minimize interaction with products (for example, assembling sandwiches [50]), as well as packaging [51]. A new stage in the development of this technology is its implementation in the grasping and manipulating of soft tissue [11] in medical robotics (Fig. 2c), and using liquid as an energy source for grasping [52].

Vortex jet gripper technology has many advantages, allowing the desired lifting effect on the finger to be achieved, thereby enhancing dexterity during manipulation. To achieve this, it is necessary to integrate the vortex gripper into the fingertip of a dexterous gripper, while providing:

- Fabrication of the vortex integration part from soft materials to ensure adaptability during finger compression and increase frictional properties between the object and the fingertip;
- Minimization of the vortex gripper size, to allow integration into the fingers (identical to the average human size) of the dexterous gripper;
- Study into the influence of the fingertip soft elements' shape on the lifting force, which allows selecting the optimal parameters of the gripper for better dexterity.

These factors all influenced the design of the vortex gripper presented in this paper.

III. ROBOT FINGER MOUNTED VORTEX GRIPPER

A. Soft Vortex Gripper

1) Dimensions: The primary constraint in fabricating the vortex gripper was ensuring it could be mounted directly onto the fingertip of a robotic hand. This required minimizing both the gripper's diameter and depth for seamless integration. We built off of prior work [11], which introduced the idea of using a rigid vortex gripper for safely manipulating soft tissue. The previous gripper design has an external diameter of 26 mm and a total height of 19 mm; we found these parameters too large for the new application. To address the size constraint, we reduced the overall diameter to just over 15 mm and limited the main body height to 4 mm, enabling straightforward integration without visibly altering the finger's profile (Fig. 3). Despite the reduced size, the friction element length was preserved for both the round and square gripper variants, while the tapered geometry was re-dimensioned to 1.5 mm to suit the smaller contact area. The reduction in overall gripper size also led to a proportional rescaling of the interior vortex cavity. Since this study explores different surface geometries, each gripper variant features slight dimensional differences: the round gripper has a curved contact surface with a radius of 1.75 mm (Fig. 3c), the tapered variant features a front surface angled at 40.9 degrees (Fig. 3b), and the square gripper retains a flat face without additional surface modifications (Fig. 3a).

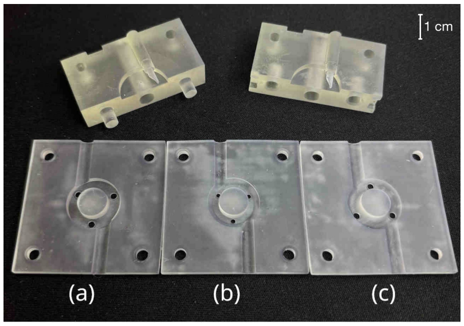


Fig. 4: Three-piece mold used to silicone cast all of the different grippers including square (a), tapered (b) and round configurations (c), respectively.

2) Fabrication: The miniaturized soft vortex gripper was fabricated primarily through silicone molding. The molds were constructed in three parts to accommodate the horizontal orientation of the nozzle inserts relative to the vertically aligned main air cavity. To allow clean molding, we designed the pieces to be screwed together to minimize silicone leakage between mold faces. We opted to use the Form 3+ SLA printer with a layer thickness of 0.05 mm for the mold production (Fig. 4). This combination provided the necessary resolution to easily print the complex curvature in the molds. Clear V4 resin was used due to its transparency, allowing for easy detection and removal of air bubbles during silicone injection. After fabricating the molds, we decided to use Dragon Skin 30 due to its Shore hardness of 30A. This

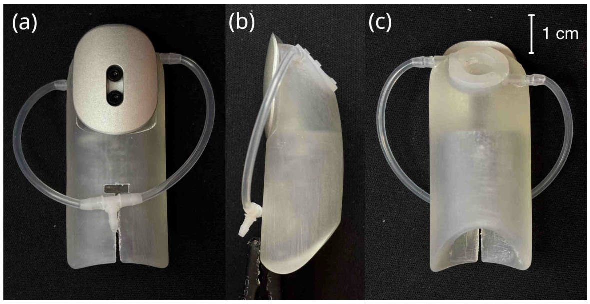


Fig. 5: Top, side, and bottom profile of the rigid finger with embedded soft vortex gripper.

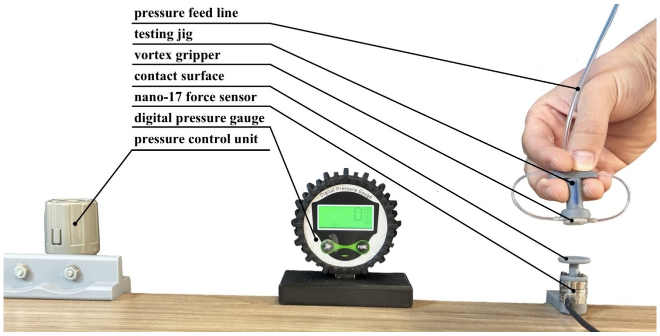


Fig. 6: Experimental setup to collect the force vs. pressure data.

allowed the grippers to have the flexibility of a needle to conform to objects while also giving it the strength needed to form reliable vortices. For all three gripper geometries, the same bottom half of the mold was used, with only the top surface geometry swapped out, ensuring that the only variable across designs was the contact surface shape.

B. Design of Rigid Finger

We also designed a rigid finger that would house the vortex gripper. For the original design of the vortex gripper we used a preexisting PLATO robotic hand. We selected the PLATO hand due to its availability in the lab and its two-degree-of-freedom control per finger, enabling human-like grasping and fingertip motion. The robotic hand had soft silicone fingers that we brought into CAD and began modifying to create our own vortex gripper integrated robotic finger.

1) Design Modifications: To allow integration of the soft vortex gripper into the robotic hand, the rigid finger design was modified to accommodate the gripper's addition. A cavity was added into the fingertip with a depth of 4 mm and a diameter of 20 mm. This cavity provided just enough space to securely seat the gripper and have it blend seamlessly into the fingers' geometry. The cavity was angled at 45 degrees, selected based on its effectiveness in maximizing gripping force and control during contact [53], [54]. Rigid nozzles with barbed fittings were added to the interior edges of the cavity to serve as air inlets, with an internal diameter of 1 mm. The nozzles were SLA printed along with the rigid finger to guarantee the ability to support high-velocity airflow without deformation. The addition of the cavity required a slight redesign of the mounting bracket, which now features a slanted front edge to free up space for the gripper implementation. Care was taken to maintain compatibility with the original aluminum fingernail and nano force sensors. These changes were made with a focus on seamless integration, allowing the finger to maintain all original functionality while supporting the added capabilities of the vortex gripper.

2) Assembly: The modified finger was SLA printed to ensure the small internal geometries were printed with enough precision for proper fit and function. We used the Form 3BL with Clear V4 resin and a layer thickness of 0.1 mm. The clear resin's transparency provided the ability to visually inspect the internal channels during assembly. To preserve the tolerance of the 1 mm diameter nozzles, the fingers were oriented with the nozzles vertically during printing to minimize shrinkage, a known issue in SLA printing. This orientation also maintained sufficient tolerances required for the internal mounting features. The mounting brackets were printed in the same manner and were oriented with the flat mounting surface facing the build plate to reduce deformation and allow for a clean mounting surface. After printing the rigid finger, we attached a T-shaped barb fitting and flexible tubing to the nozzles to merge the two nozzles into a single feed pressure line. This maximized the simplicity of the pneumatic system and prioritized quick interchangeability between finger variants. The soft vortex gripper was seated into the internal cavity, completing the finger assembly. The final steps involved attaching the rigid finger to the PLATO hand [55]. This involved securing the mounting bracket to the nano force sensor, sliding the bracket into the finger, and using the aluminum fingernail to tightly secure the finger to the hand. The final assembly of the vortex gripper-embedded finger can be seen in Fig. 5.

IV. EXPERIMENTAL METHODS

A. Lifting Force Studies

The goal of this experiment was to test how different gripper face geometry would affect lifting force. We tested three different designs, which were square, tapered, and round gripper shapes (include reference here to the figure). To keep data collection consistent and simple, we developed a simple lifting force test using an ATI Nano-15 force sensor, chosen for its compact size and high accuracy.

We also designed our own attachments to screw to the force sensor to allow for more reliable data collection. We PLA printed a clamping device that attached to the bottom of the sensor that we used to secure the device to the testing table, ensuring the force sensor did not move during data collection. We also added a flat and smooth top plate to the force sensor to ensure the vortex gripper had a solid contact surface to make contact with. We also designed a testing jig to help hold and guide the gripper, which included a cutout for inserting the gripper and two handles for pulling it vertically, similar to the geometry of a syringe (See Fig. 6). This design allowed for consistent normal force application and minimizing variation in the angle of approach.

(a) Jenga Experiment (b) Card Lifting Experiment

Fig. 7: Experimental setup to test the fingers' ability to: (a) pull Jenga blocks from a supersized model; (b) pick up singular cards from a deck.

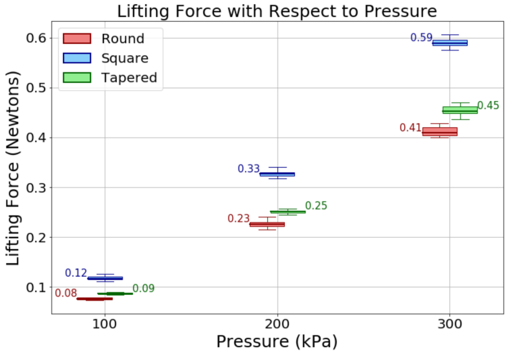


Fig. 8: The Force vs. Pressure plot for each gripper shape.

To study the effects of pressure, each gripper shape was tested at 100, 200, and 300 kPa. For each shape and pressure level, we collected ten data points to show the grippers average lifting force and consistency. During each trial, the gripper was slowly brought into contact with the contact surface of the force sensor, then pulled away until suction was lost. The peak force was recorded and compiled into a box plot to visualize the results.

B. Dexterity Experiments

1) Pulling Block: The goal of this experiment was to evaluate how the integration of the vortex gripper improved dexterity in tasks involving confined object manipulation, such as pulling a block from a tower or grasping items in tight orientations. Many modern-day grippers struggle with these applications due to the demand for high precision.

To test this idea, we used a Jenga block tower and performed six trials where blocks were pulled from a fully built tower without any pre-loosening. The smaller block size of the Jenga tower provided a smaller gripping surface on the block, increasing the intricacy and precision needed to remove the block. During this experiment we ran trials using one vortex gripper-embedded finger and a silicone control finger. The silicone control finger allowed us to obtain a baseline performance for a robotic hand made to model human fingers. We tested this soft robotic finger against the vortex gripper-embedded finger to see any visible signs of improvement in dexterity.

When conducting the experiment, we pulled the same two blocks from the Jenga tower to eliminate the difference in surface friction from being a variable in the experiment (See Fig. 7a). We also picked two blocks from the same side of the Jenga tower with the same method in order to get a better gauge on gripper consistency. All of these experiments were conducted in the same block order and at 300 kPa to eliminate as many external factors as possible.

2) Grasping Single Card: This experiment was used to test the advantages the vortex gripper would have when grabbing flat, thin objects from a flat surface. This is a very common issue in most robotic hands because a task such as picking up a piece of paper from a table requires a lot of fine motor skills. In order to test this theory, we used a deck of playing cards on an elevated surface to test out the improvements in dexterity. We chose a deck of playing cards due to their slippery texture as well as their construction from a thicker paper material. This provided multiple unique challenges, such as decreased surface friction and an inability to bend the cards.

For the setup of this experiment we had a full deck of playing cards on an elevated surface (See Fig. 7b). We ran this experiment for 15 trials with the vortex gripper-embedded finger and the silicone control finger, allowing us to see what improvements the vortex gripper-embedded finger had in comparison to a common traditional robotic finger. For all of the trials, we attempted to remove playing cards from the deck one at a time. For all of the vortex gripper-embedded finger trials we used a pressure supply of 150 kPa to give us ample gripping strength but minimal disturbances of our surroundings. All of the fingers were teleoperated by the Roboligent OPTIMO 7-DOF robotic arm. In all of the gripper-equipped trials, we slowly approached the deck of playing cards until we made contact with the card at the top of the deck; we then attempted to remove the top playing cards one at a time without disturbing the rest of the stack. For the soft silicone finger trial, we attempted the same approach but attempted to utilize the fingernail of the finger to allow for the highest chance of success.

V. RESULTS AND DISCUSSION

A. Lifting Force Studies

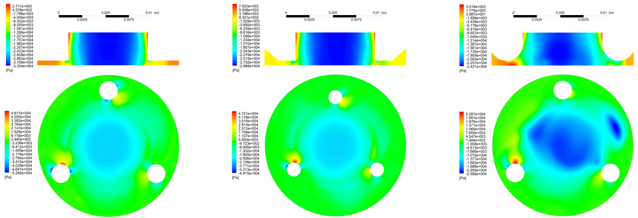
The relationship between shape, pressure, and lifting force was analyzed to identify trends in gripper performance. Across all tested pressures, the Square shape exhibited the highest mean Lifting Force, followed by the Tapered and Round Shapes. The corresponding box plots of the recorded data in Figure 8, further illustrate these trends. The summary statistics for Lifting Force, categorized by Shape and Pressure, are presented in Table I.

To assess statistical significance, a two-way ANOVA was conducted to evaluate the effects of the independent variables (Shape, Pressure) and their interaction on Lifting Force. The results are summarized in Table II.

The two-way ANOVA indicated that both main effects and the Shape × Pressure interaction were statistically significant, demonstrating that at least one group differed from the others. Because the Shape × Pressure interaction was significant, interpretation of the main effects of Shape or Pressure

TABLE I: Summary statistics of the dependent variables

Shape	Pressure (kPa)	Force (N)	Std	Min	Max
Round	100	0.076	0.002	0.073	0.078
Round	200	0.226	0.008	0.214	0.240
Round	300	0.412	0.010	0.400	0.428
Square	100	0.117	0.004	0.110	0.126
Square	200	0.327	0.007	0.317	0.340
Square	300	0.590	0.009	0.576	0.607
Tapered	100	0.086	0.002	0.084	0.088
Tapered	200	0.251	0.004	0.245	0.256
Tapered	300	0.454	0.011	0.436	0.470



(a) Square Gripper (b) Tapered Gripper (c) Round Gripper

Fig. 9: Finite element method results (pressure distribution along the cross-section of the gripper axis and the object surface) of the three studded vortex gripper devices at a supply pressure of 200 kPa: (a) Square; (b) Tapered; (c) Round.

independently could be misleading. Therefore, the post-hoc analyses focused on the simple effects within each level of the other factor. To identify specific group differences, Tukey's HSD post-hoc tests were performed for Shapes within each Pressure. The results are reported in Table III

The post-hoc analyses confirmed that all pairwise comparisons between Shapes were statistically significant across the tested Pressures. These results consistently show that the Square shape produced the highest Lifting Force, followed by Tapered then Round.

Using the turbulent shear stress transport (SST) model, computational fluid dynamics - finite element method [42], [43], [47], we can analyze the air pressure distribution over different surfaces of grippers of various shapes (Fig. 9). For the case of a vortex gripper, we are interested in the pressure distribution along the axial cross-section of the gripper and along the surface of the object. We can see a clear connection with the uniformity and stability of the negative pressure on the cross-section of the square gripper (Fig. 9a), which provides the greatest lifting force (Fig. 8). On the other hand, tapered (Fig. 9b) and round (Fig. 9c) grippers have a non-uniform distribution of negative pressure along the cross-section axis, which causes a drop in the lifting force for all ranges of supply pressure (Fig. 8). It is also worth noting that the non-optimal placement of the friction elements in the gap between the vortex gripper and the object causes additional vortices. These vortices form zones of positive and negative pressure around the friction elements, which in turn negatively affect the lifting force of the vortex gripper.

B. Dexterity Experiment

1) Pulling Block: The fingers' ability to remove Jenga blocks from the tower was evaluated based on the block removal time, the forces exerted during the task, and the overall success rates. These results are summarized in Table IV.

TABLE II: Two-way ANOVA results

	DF	F-value	p-value	η_p^2
Shape	2.0000	1896.6567	9.37e-69	0.0733
Pressure	2.0000	23406.4798	1.30e-112	0.9048
Shape:Pressure	4.0000	262.3296	1.68e-45	0.0203
Residual	81.0000	NaN	NaN	0.0016

TABLE III: Tukey HSD post-hoc test for Shapes at each Pressure

Pressure	Group 1	Group 2	Mean Diff	p-value	Sig
100	Round	Square	0.0413	0.000	True
	Round	Tapered	0.0103	0.000	True
	Square	Tapered	-0.0310	0.000	True
200	Round	Square	0.1016	0.000	True
	Round	Tapered	0.0252	0.000	True
	Square	Tapered	-0.0764	0.000	True
300	Round	Square	0.1786	0.000	True
	Round	Tapered	0.0421	0.000	True
	Square	Tapered	-0.1364	0.000	True

The vortex gripper-embedded finger showed significantly better performance than the silicone control finger. On average, it required less than half the time to extract single blocks and achieved a 100% success rate, compared to the 66.66% success rate observed for the silicone control finger.

This reduction in block removal time and improvement in success rate exemplifies the advantages of the vortex gripper design. The shorter task duration suggests that the addition of the vortex gripper simplified the block extraction, enabling the operator to complete the task more efficiently. The silicone finger however, required more precision and delicacy, leading to longer task times and increased difficulty during block removal.

The higher success rate of the vortex gripper embedded-finger demonstrates its ability to extract constrained objects. Compared to the silicone control finger, the vortex gripper showed 33.33% improvement in grasping.

There was also a very clear distinction in extraction approaches among the different finger types. The silicone control finger needed to utilize the side of the finger and push the block out of the tower, while the vortex gripper was able to use its suction to pull blocks instead (See Fig 10 (a)-(c)). The difference in extraction techniques stems from the added functionality of the vortex gripper. The suction force allows the finger to both push and pull the Jenga block giving it more versatility. This added capability not only improved efficiency but also reduced the likelihood of task failure, proving the advantages of the vortex gripper in precise and constrained object manipulation.

2) Grasping Single Card: To evaluate the improved dexterity of the vortex gripper-embedded finger, we analyzed its success rate in removing a single card from the top of a deck, as well as the forces exerted during the task. The success rates for both finger types are presented in Table V.

The results reveal that the vortex gripper significantly outperformed the silicone control finger, achieving a success

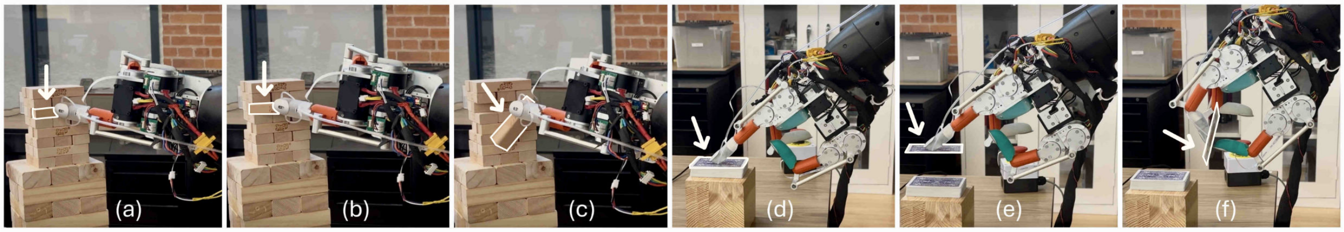


Fig. 10: Sequence of images showing stages of pulling out a block (a-c) and picking a single card from a deck (d,e,f) using the soft square vortex gripper.

TABLE IV: Avg. Block Removal Time and Success Rate

	Removal Time (s)	Success Rate (%)
Control Finger	11.385	66.66
Vortex Gripper	4.267	100

TABLE V: Avg. Cards Removed and Success Rate

	Average Cards Removed	Success Rate (%)
Control Finger	3.33	33.33
Vortex Gripper	1.07	93.33

rate of 93.33% over 15 trials. This was over nearly three times higher than that of the control finger. This consistency to remove a single card shows the vortex gripper's capability to handle thin, flat objects. This task still remains challenging for many other robotic hands.

There were also differing approaches needed for the control finger and vortex gripper-embedded finger to complete the task. The silicone control finger required the use of its fingernail and applied additional force to the deck due to the complexity of the task. The vortex gripper, however, made only light contact with the deck before delicately lifting the card (See Fig 10 (d)-(f)). This illustrates the griper's ability to complete intricate and precise tasks with ease.

VI. CONCLUSION AND FUTURE WORK

This work highlights the advantages of the vortex gripper-embedded finger in tasks requiring both strength and dexterity. In the lifting force experiments, the square-shaped gripper geometry consistently outperformed the other shapes, producing the highest mean lifting force, by over 30%, across all pressures. Statistical analysis confirmed the significance of shape and pressure, with the square design proving optimal for maximizing performance.

In dexterity-focused tasks, the vortex gripper demonstrated highly improved performance in comparison to a silicone control finger. It reduced Jenga block removal time by more than half and achieved a perfect 100% success rate, compared to 66.66% for the soft robotic finger. Additionally, in the card-grasping experiment, it achieved a 93.33% success rate, nearly three times higher than the control finger, by delicately lifting thin, flat objects with minimal force. These results showcase the gripper's ability to handle both constrained and intricate tasks with precision and reliability.

The combination of high lifting force and dexterous manipulation positions the vortex gripper as a versatile tool for soft robotic applications. Future work will focus on refining the design and implementing the vortex gripper into more complicated robotic systems. Furthermore, our approach to designing a novel robotic subsystem, inspired by the functions of the human skin which not currently not available to robots, opens the door to infusing existing robots with new, human-like capabilities.

ACKNOWLEDGMENT

This work was supported in part by Texas Robotics through an Industrial Affiliate Program Seed Fund.

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