Low-Contact Grasping of Soft Tissue Using a Novel Vortex Gripper

Roman Mykhailyshyn[1] and Ann Majewicz Fey[2]

***Abstract*— Manipulation of soft tissues remains one of the most prevalent tasks during minimally-invasive surgery. However, surgical instruments for soft tissue grasping are primarily composed of hard, metallic materials which could result in tissue damage, if not properly used, as well as require large contact areas, both locally during grasping, as well as across the entire organ during large manipulation tasks (e.g., running bowel). As an alternative to traditional pinch-type graspers for tissue manipulation, vortex technology, currently found in manufacturing applications with fragile materials, could hold great promise. Vortex technology creates a negative pressure vortex through the ejection of compressed air through a specialized nozzle. This technology enables low-contact grasping of materials, including those at a distance and even through levitation of objects. Unlike suction cups, vortex grippers are also capable of grasping complex, non-smooth surfaces. In this paper, we present the design of a vortex gripper for soft tissue manipulation. We investigate the force characteristics of this gripper in grasping soft objects with four common shapes of varying radii of curvature and also evaluate the gripper's performance in grasping bio-inspired, artificial intestine tissue. Finally, the paper concludes with proposed design enhancements for future use in applications with biological tissue.**

I. Introduction

While understanding and measuring contact force during surgery is still a developing area of research [1], evidence suggests that expert surgeons typically apply less force to tissue than novice surgeons. Minimizing force applied to tissue is important during surgery as studies have demonstrated that high tissue grasping forces lead to the destruction of endothelial and smooth muscle cells [2], increase the risk of irreversible tissue changes [3], [4], and elevate the likelihood of adhesion formation after surgery [5]. Post-surgical adhesions can have devastating long-term consequences for patients including pain, bowel obstruction, and infertility [6]. As such, there has been significant interest to incorporate force sensing capabilities with surgical graspers [7], [8]. Animal studies have also shown that the addition of a tactile haptic feedback device, designed to reflect grasping forces to the user, can significantly reduce both grasping force and tissue damage [8]. While promising, this technique requires the use of custom sensors which are not yet widely commercially available. An alternative approach could be to design novel tissue graspers which are not capable of producing such high, damaging forces.

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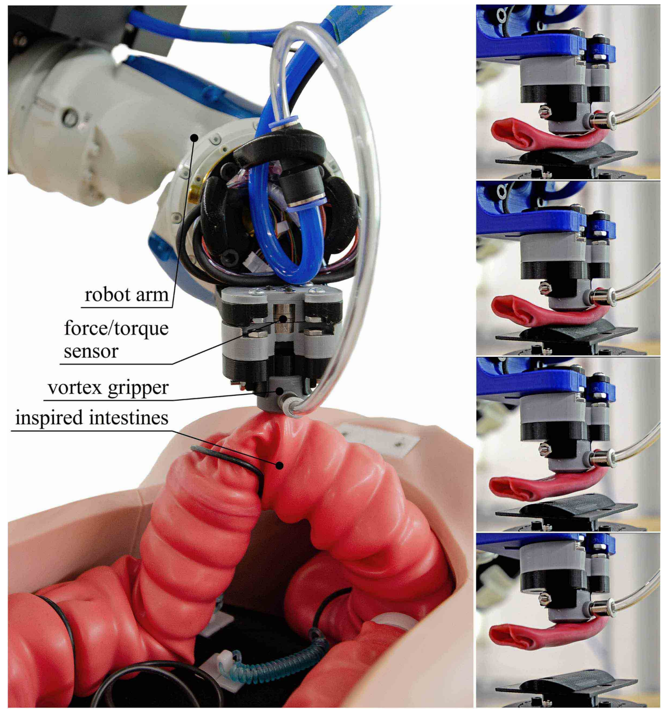


Fig. 1: Vortex-based low-contact grasping of bio-inspired intestine using the Colonoscope Training Simulator (Kyoto Kagaku).

Currently, surgical applications predominantly use only a few types of gripping devices including mechanical grippers using various drive mechanisms [9] and vacuum-based grippers that use suction cups of various designs [10]. Mechanical grippers remain the most common type of surgical grasper with some recent advances in the literature to incorporate more compliant mechanisms [11], [12] and elastic actuators [13]. However, even these compliant mechanisms can be shown to damage tissue, even if at small scales [14]. There is also growing interest in developing soft grasping mechanisms for surgical applications such as soft pinch-type graspers or hooks [15] and three-fingered grippers [16], [17]. While soft, compliant mechanisms are promising to reduce grasping forces, their ability to precisely control that force is not well understood.

Alternatively, pneumatic jet technologies present a viable option for medical grasping applications. Within the spectrum of pneumatic jet gripping devices [18], [19], vortex and Bernoulli grippers are particularly promising due to their high reliability, prolonged service life, and economical manufacturing costs. In addition, a very unique aspect of these gripping devices is their ability to grasp of objects with and even without physical contact, as well as robustness to the type of material grasped and it's mechanical properties and surface structure, as well as robustness to environmental temperature changes.

Jet gripping devices are most commonly used for handling fragile items such as solar panels [20], silicon plates [21], [22], and glass materials [23], or for flexible objects like packaging materials [24], textiles [25], [26], and items with complex shapes like fruits [27], leather products [28], and objects with perforations such as electronic boards [29]. Recently, Bernoulli-type grasper have been developed for potential applications in laparoscopy surgery [30], [31], but these graspers have yet to be demonstrated through rigorous experiments with real or simulated biological tissue.

Among all jet gripping devices, vortex gripping devices demonstrate the least sensitivity to the surface roughness and shape of the grasped object, particularly concerning their holding force. Unlike Bernoulli gripping devices where the airflow is directed at the object, vortex grippers feature nozzles positioned tangentially to the gripper cavity. The centrifugal force generated within the vortex confines the airflow, thereby minimizing direct interaction with the object's surface. This unique characteristic makes these grippers a preferred choice when handling electronic boards hosting diverse components or when attaching to objects with significant surface roughness [32].

This paper introduces a novel approach: applying 3D printing technology to fabricate vortex grippers tailored for medical applications. This innovation leverages the technology's advantages to reduce contact between the robot and tissue. Achieving the highest precision in manufacturing the gripper's nozzle elements through SLA 3D printing relies on their orientation relative to the printing plane. Our research findings demonstrate that the vortex gripper is capable of securely grasping soft objects of diverse shapes (Fig. 1). Furthermore, it shows substantial robustness and increased gripping force, capable of lifting loads up to 3.5 N at 400 kPa - more than 35 times the gripper's weight. Finally, during experiments involving the handling of bio-inspired intestines, it became evident that adding frictional elements was necessary to prevent tissue slippage and further enhance the lifting force, thus our paper ends with a recommendation for a redesign of the proposed vortex gripper that will be better able to grasp real biological tissue.

II. Methodology and Material

The vortex gripper boasts a well-established design renowned for its capability to handle delicate objects like silicon and solar panels in manufacturing settings. However, adapting such a gripper for medical applications poses numerous limitations. The primary challenge lies in its downsizing while ensuring sufficient lifting force to manipulate soft tissues. To establish initial parameters, we selected the dimensions of intestines (commonly manipulated in trauma scenarios) with an average statistical minimum radius of 15 mm [33]. Consequently, it was imperative to constrain the gripper body dimensions to not exceed 26 mm.

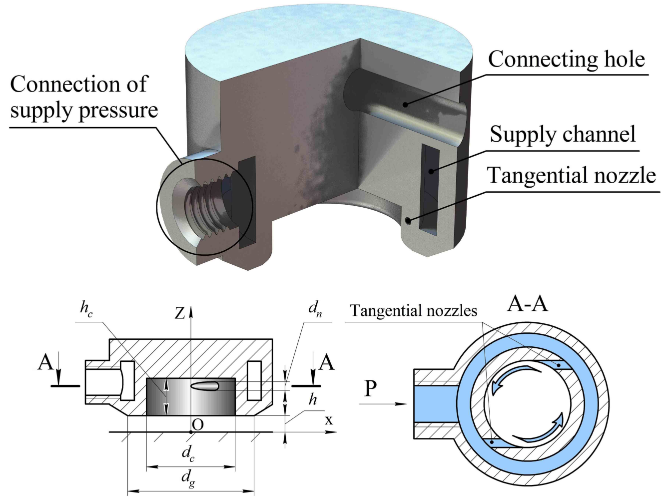


Fig. 2: The proposed design of the gripper (with parameters indicated: d_g - gripper diameter, d_n - nozzle diameter, d_c - cavity diameter, h_c - cavity height, h - the gap between the gripper and the object).

The operation of the vortex gripper involves supplying compressed air (or liquid) P through the connector in the gripper body (Fig.2). Subsequently, the compressed air enters the supply channel (essential for maximum force characteristics [34]), which connects to two cylindrical nozzles (with a nozzle diameter d_n) directed tangentially towards the cylindrical gripper cavity with a diameter d_c and height h_c. As the compressed air exits through these nozzles and the gripper cavity's cylindrical shape guides the airflow direction, rotation initiates (Fig.2). This rotational movement imparts angular velocity and centrifugal force to the airflow, generating negative pressure on the object's surface within the d_c zone opposite the cavity. Simultaneously, positive pressure forms in the object zone opposite d_g-d_c (the active surface of the gripper). Given that the negative pressure zone's area significantly surpasses that of the positive pressure zone and the resultant negative pressure exhibits a greater difference with atmospheric pressure than the positive pressure, it leads to the generation of lifting force. A simplified equation for calculating the lifting force of a vortex gripping device is outlined in [21]:

$$F_l = \frac{1}{4}\rho\pi\omega^2\left(\frac{d_c}{2}\right)^4, \tag{1}$$

where ρ is the air density (kg/m^3), $\omega = 2u_\alpha/d_c$ is the air angular velocity (1/s), and u_α is the circumferential velocity (m/s).

Given the size limitations, we chose the following parameters for the gripper for further research: $d_n = 0.8$ mm, $d_g = 20$ mm, $d_c = 14$ mm, $h_c = 4$ mm. SLA 3D printing (Formlabs Form 3+) was chosen for the fabrication of vortex gripping devices, thanks to which it is possible to achieve the highest accuracy (print height 25 μm) of the manufacturing of small parts of the prototype.

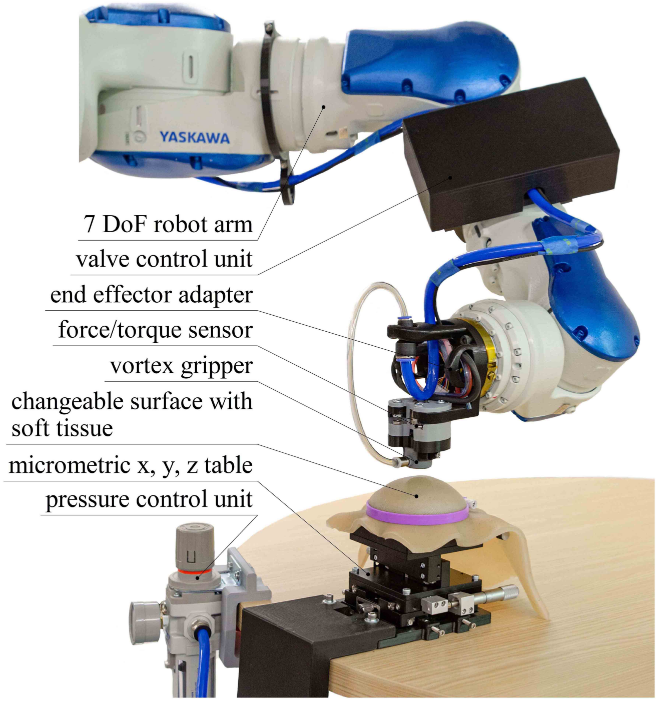


Fig. 3: Experimental setup for studying the force characteristics of a vortex gripper.

To assess the impact of soft object and tissue shape parameters on the lifting force exerted by vortex grippers, it's essential to identify the surfaces that these grippers will interact with during surgical applications. For instance, consider one of the most common trauma surgery procedures involving the lifting and manipulation of intestines. The radius of the intestines varies from 15 mm for the smallest intestine to less than 45 mm for the largest cecum [33]. Depending on their filling, spatial positioning, and interaction with other organs and tissues, intestines generally exhibit four different surface shapes: dome (convex), cylinder (convex), dome (concave), and cylinder (concave).

To develop a comprehensive understanding of vortex grippers' suitability for grasping soft tissues in medical settings, it's recommended to conduct studies encompassing four surface types and varying surface radii (r_c) within the ranges typical for intestines (15, 20, 25, 30, 35, 40, 45 mm) as well as beyond—50, 75, 100 mm, and flat surfaces (typical for other tissues).

To evaluate the force characteristics of the newly developed vortex gripping devices with various soft-surfaced objects, an experimental setup was developed (Fig. 3). This setup includes a 7 Degree of Freedom (DoF) Yaskawa SDA10F robot arm with an attached valve control unit and an end effector adapter. A vortex gripping device is affixed to the end effector adapter using an ATI Nano17 force/torque sensor with measurement limits for F_x and F_y 25 N for F_z 35 N, boasting an accuracy of ±0.25%. Additionally, a compressed air pressure control unit and a micrometric x, y, z table are fixed to the surface. Alterable surfaces accommodating soft bio-inspired tissue [35] are mounted onto the micrometric x, y, z table for experimentation.

To assess the lifting force of the vortex gripping device, the desired compressed air pressure value (100, 200, 300, or 400 kPa) is selected using the pressure control unit. Following this, calibration of the force/torque sensor is conducted. Subsequently, utilizing the robot arm, the vortex gripper is vertically positioned at the center of the designated surface until the F_z value of the force/torque sensor reaches approximately -2 Newtons. This indicates that the vortex gripper has made contact with the object, causing deformation of the soft bio-inspired tissue.

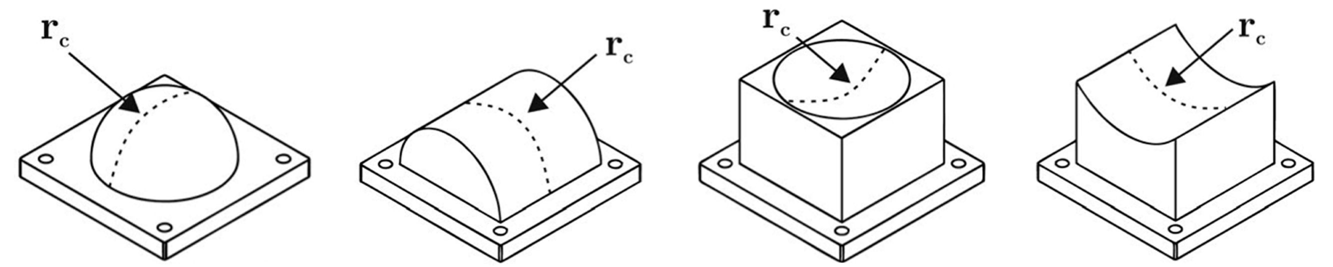
Subsequently, the valve supplying compressed air to the vortex gripping device is activated. As a response to the compressed air pressure supply, the F_z indicator of the force/torque sensor decreases, signifying the closure of the gap between the gripper and the object. Following this, the vortex gripping device ascends vertically (at a velocity of 0.01 m/s and acceleration of 0.01 m/s^2), initiating the data collection of force characteristics (F_z). Data collection starts from the point when $F_z = 0$ and continues until the gripper ascends beyond a distance of 100 mm from the object. This experimental procedure is repeated 10 times for the same surface and pressure settings.

III. Results and Discusion

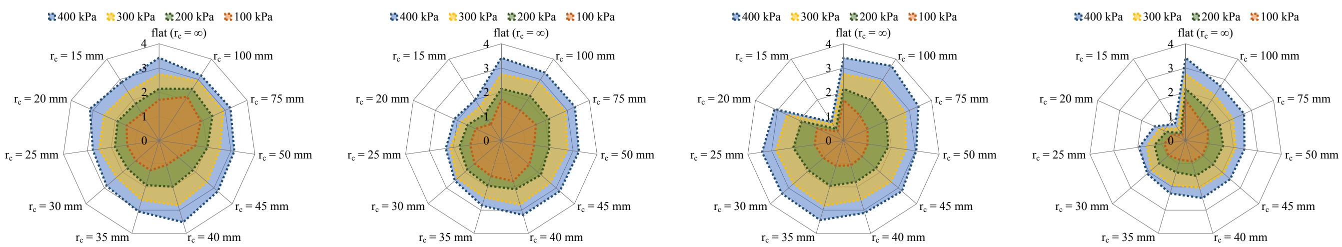
During experimental studies aimed at determining the lifting force of a vortex gripper for soft objects with varying shapes, we got the F_z force distribution throughout the gripper's vertical movement. Conducting 10 experiments under identical parameters (pressure and surface) enabled us to derive the average distribution of the lifting force F_z during the gripper's vertical motion. This distribution serves as a basis to ascertain the average maximum lifting force (F_l^{max}) achievable by a vortex gripper possessing a suitable surface under specific supply pressure. To identify this maximum lifting force, a comprehensive experiment was conducted (refer to Fig. 4) encompassing four supply pressures (100, 200, 300, and 400 kPa) and 41 soft surfaces varying in radius and type.

The distribution of lifting forces across all surfaces indicates that the most consistent force is sustained when grasping the dome's concave soft surface (Fig. 4e). This stability results from the design of the vortex gripper, featuring a cavity and a rounded transition chamfer from the cavity to the gripper's flange, enabling the convex surface of the dome to fit within this cavity. This essentially maintains a consistent gap between the surface and the gripper. Similarly, for dome concave surfaces, a uniform gap formation persists (Fig. 4g). However, beyond a radius of 20 mm, the lifting force significantly decreases. This reduction occurs because there isn't enough space between the gripper body and the soft surface to facilitate the exit of air supplied through the vortex gripper's nozzle elements.

From (Fig. 4f), it's evident that the lifting force exerted by the gripper with a cylindrical convex surface is lower than that of the dome-shaped gripper. This disparity arises from the unevenness in the gap between the gripper and the soft surface. As the radius of the cylindrical surface decreases, the lifting force diminishes. This decline can be attributed to the

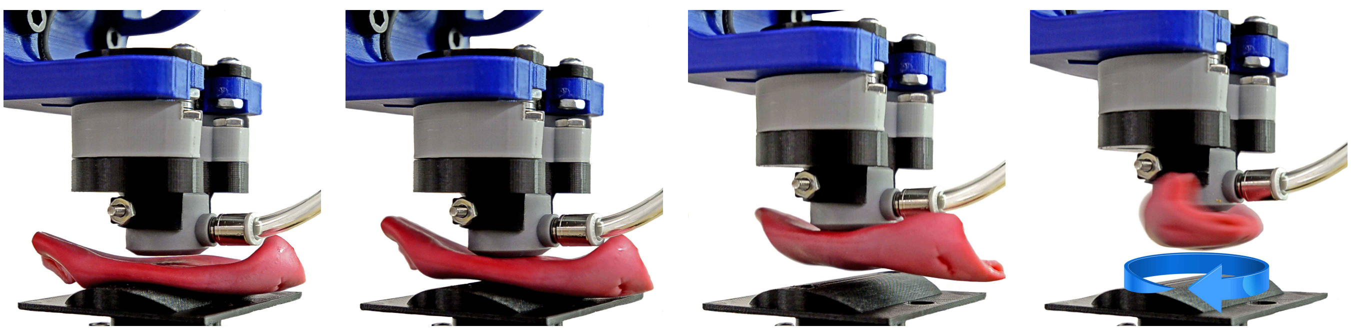


(a) dome (convex) (b) cylinder (convex) (c) dome (concave) (d) cylinder (concave)

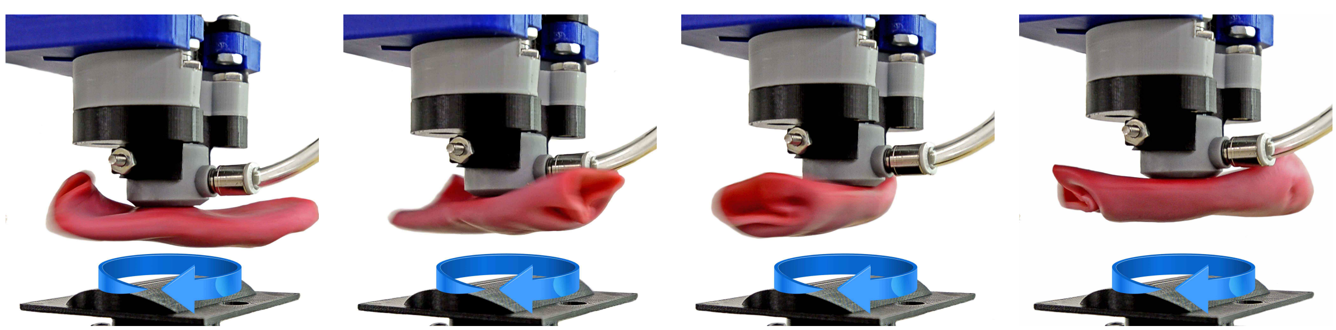


(e) dome (convex) (f) cylinder (convex) (g) dome (concave) (h) cylinder (concave)

Fig. 4: Characteristics of the lifting force (N) of vortex gripper with soft tissues surfaces of different radius (mm) and supply pressure (kPa): where horizontally gripper with $d_n = 0.8$ mm - e, f, g, h, and vertically the type of surface (Dome (convex) - e; Cylinder (convex) - f; Dome (concave) - g; Cylinder (concave) - h).



(a) (b) (c) (d)



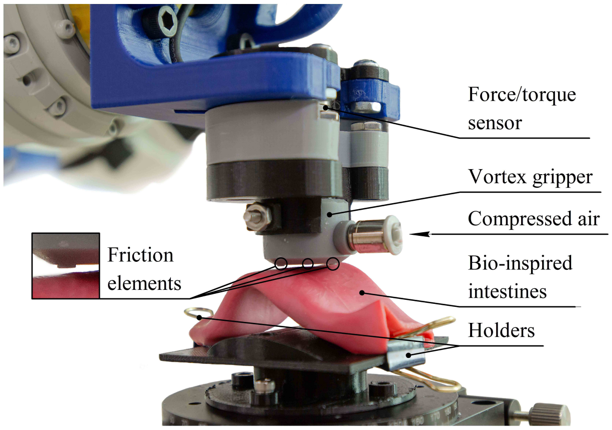
(e) (f) (g) (h)

Fig. 5: Grasping (a-b) and lifting (c-h) bio-inspired intestines, which led to their rotation under supply pressure of 200 kPa.

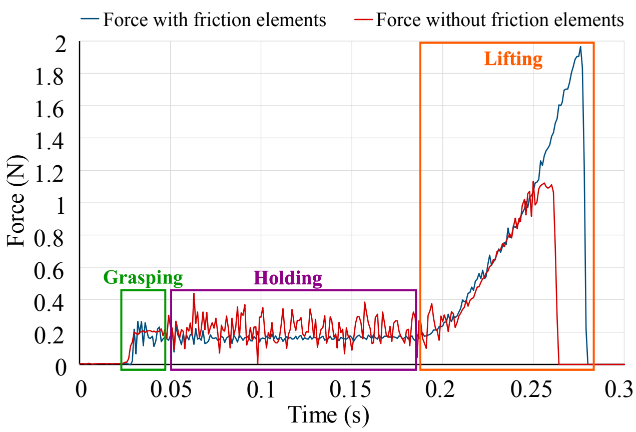
widening gap between the surface and the gripper. Similar dynamics occur for a cylindrical concave surface (Fig. 4h). However, in comparison to the cylindrical convex surface, the region of the gap affected by the cylindrical surface's interference with airflow expands, leading to an even greater reduction in the vortex gripper's lifting force.

A. *Bio-Inspired Intestine Evaluation*

A bio-inspired intestine measuring 15 mm in diameter and 120 mm in length served as the test subject to assess the efficiency of the vortex gripper in grasping and lifting soft tissue. The gripping device was positioned parallel to the bio-inspired intestine at a 3 mm distance (Fig. 5a). Subsequently,



(a)



(b)

Fig. 6: Grasping, holding, and lifting of bio-inspired intestine fixed at two ends: (a) experimental setup and vortex griper with frictions elements; (b) force parameters at a supply pressure of 300kPa.

a pressure of 200 kPa was applied to the gripping cavity, causing the bio-inspired intestine to be attracted toward the gripper (Fig. 5b). Following this, the gripper moves up, lifting the bio-inspired intestine (Fig. 5c-h). As the bio-inspired intestine was lifted, starting from the moment it lost contact with the surface (Fig. 5c) on which it lay, it began to rotate (Fig. 5d). This rotation stemmed from the vortex airflow generated by the gripper, easily inducing rotation in various objects during non-contact manipulation. Additionally, the intestine's innate deformability allowed it to adapt to the airflow, preventing direct contact between the gripper and the intestine. Consequently, upon losing contact with the surface, the intestine continued rotating until it either slipped off or disengaged from the gripper.

The decision was made to incorporate three friction elements onto the gripper's active surface, each measuring 2 mm in diameter, 0.4 mm in height, and spaced 120 degrees apart. This configuration represents a conventional solution for this types of grippers [36]. Additionally, an experiment was conducted to determine the lifting force of the secured bio-inspired intestine from both ends (Fig. 6a). For comparative purposes, two types of developed grippers - one with friction elements and one without were utilized. These grippers were used to grasp, hold, and vertically lift the intestine until contact was lost, under a supply pressure of 300 kPa. The force parameters obtained from the comparative experiment are presented in Fig. 6b.

From the results in Fig. 6b, it is evident that both grippers exhibit similar force parameters during the grasping phase. However, the gripper lacking friction elements exhibit fluctuating force parameters while holding, indicating intestine vibrations. These vibrations occur because the intestine deforms under the gripper's force, attracting it, but if the gap between the tissue and the gripper is too small, significant pressure builds up, causing the tissue to oscillate in the opposite direction. Intestinal vibrations not only endanger the gripper's ability to maintain hold but also pose a risk of damaging soft tissues. In contrast, using a gripper with friction elements practically eliminates intestinal vibrations (Fig. 6b). The presence of these elements restricts tissue deformation towards the gripper and limits vibrations. Moreover, the friction elements increase lifting force by minimizing intestinal slippage during lifting. With a supply pressure of 300 kPa to the gripper chamber, the lifting force for the gripper used with friction elements increases by 77%, from 1.1 N for the gripper without friction elements to 1.95 N.

IV. Conclusion

This paper introduces a novel vortex gripper design tailored for the manipulation of various soft tissue shapes. Through conducted experiments, we studied the force characteristics associated with dome (convex), cylinder (convex), dome (concave), and cylinder (concave) surfaces. Notably, at a supply pressure of 400 kPa and with a dome (convex) surface, the vortex gripper exhibited a lifting force 35 times greater than its own weight. Despite a reduction in lifting force for different radii of the cylindrical surface, the gripper still delivered ample force to manipulate soft tissues such as intestines. Our evaluation of the vortex gripper's performance in grasping bio-inspired intestines revealed inherent issues of tissue vibration and slippage during grasping and holding. These challenges were successfully mitigated by integrating cylindrical friction elements into the gripper design. These elements effectively minimized tissue vibration and slippage, ensuring stable manipulation of bio-inspired intestines and augmenting the lifting force by 77% with a supply pressure of 300 kPa. This study contributes to delineating the limitations of vortex technology and sets the stage for its advancement in medical applications.

Our future research will focus on a comprehensive investigation into the influence of nozzle element parameters on lifting force. Additionally, we aim to develop a flexible vortex gripper tailored for minimally invasive surgical procedures. This will allow the collapse of the gripper, which will lead to the minimization of the size during the passage of the trocar and will allow it to increase for the manipulation of soft tissue in the body cavity.

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