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DESIGN AND TESTING OF A THREE FINGERED FLEXURAL LAPAROSCOPIC GRASPER

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ABSTRACT
Laparoscopic surgery requires complex manipulation and movement of internal organs. Current laparoscopic devices succeed in offering surgeons remote access to internal organs, but lack the grasping degrees of freedom achieved by the human hand. Specifically, needle nose end effectors engage organs via pinching and can cause tissue perforation. To enhance surgical capacity, a three fingered laparoscopic device was designed, fabricated and tested. Flexures are used to provide three points of articulation in each finger, while minimizing part count. Flexure joints are modeled as pseudo rigid bodies and designed for manufacture with medical grade plastics. Articulation is achieved by tendon-like control cables. To integrate with current laparoscopic procedures, the device fits through a 12mm trocar port. Furthermore, a handle was designed for this device to offer better control. Testing the device with organ-like objects revealed an increased ability to grasp, move and otherwise engage items.

INTRODUCTION
Dexterous manipulation of internal organs is central to laparoscopic surgery. These operations are performed through multiple small incisions in the abdomen. Usually between 3 mm and 12 mm wide, these incisions are held open with trocars, which serve as entryways into the body. Typically, one port provides video capability and lighting, while the others are occupied by surgical devices. The surgeon is able to manipulate internal organs using the laparoscopic devices while viewing the procedure on an external monitor. Because only a few small incisions are required, laparoscopic surgery is considered less invasive than open surgery. Minimizing trauma to the patient often results in faster patient recovery.

Laparoscopic surgery has many advantages and offers surgeons unparalleled, remote access into a patient's abdomen. However, current devices can sometimes limit a surgeon's capability. Many laparoscopic tools are derivatives of the pinching grasper seen below in Figure 1.

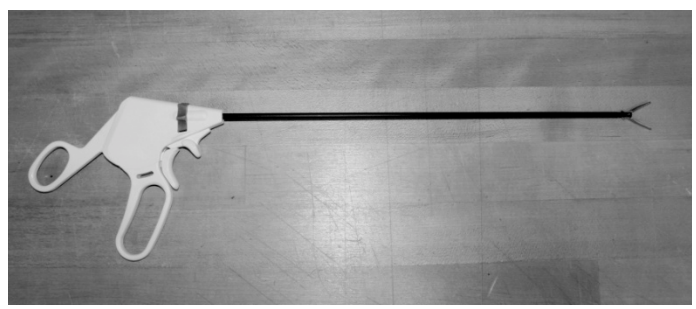

Figure 1: The pinching grasper. A sliding pin constrains the actuation of the end effector to a scissor-like pinching grip.

Operating similarly to needle nose pliers, the end effector engages an organ at a single point. As a result, high stress concentrations often lead to tissue perforation. This issue is compounded by a pinch point created by the non-parallel closing mechanism of the end effector. Furthermore, the limited surface area of the grasper increases the incidence of organs slipping from the device. In a video study of ten laparoscopic colectomies and fifteen cholecystectomies, only 62% of grasping actions resulted in clamping sufficient to perform the desired action (1). Frequent failed attempts both damage tissue and waste valuable time in the operating room. Furthermore, if surgery becomes impossible due to anatomic constraint or excessive bleeding, the laparoscopic procedure must be converted to an open surgery.

Pinching issues and tissue perforation occur to a lesser extent in open surgery and hand assisted laparoscopic surgery. However, the large incisions required for open surgical access result in increased patient trauma. Hand assisted laparoscopic surgery is a compromise solution, using an incision large enough for a single hand. The surgeon then performs the procedure using one hand as well as a separate laparoscopic device. In both of these procedures, the surgeon can engage organs manually. Human hands are capable of grasping internal structures with dexterous motion, as well as creating geometric constraints. As such, fingers typically secure objects by curling around them, rather than pinching. Therefore, manual grasping is more efficient and secure than the pinching mechanism of current graspers.

To complement the existing advantages of laparoscopic procedures, surgeons require an end effector capable of mimicking manual dexterity. This paper presents the design, fabrication, and testing of a laparoscopic device that manipulates organs by grasping instead of pinching. Fewer failed grasping attempts could lead to more efficient surgeries, replace the need for a hand port, and potentially reduce the need for conversion to open surgery. Furthermore, making the device capable of insertion through standard trocars will allow it to integrate well with current laparoscopic surgical procedures. While this device will not be appropriate for every laparoscopic procedure, the objective of this project is to enhance the laparoscopic device repertoire, always allowing the surgeon access to the most appropriate device.

NOMENCLATURE

b	Vertical component of flexure tip displacement [in]
E	Young's Modulus [psi]
F	Control cable force [lbf]
I	Area moment of inertia [in^4]
K	Flexure stiffness [lbf/in]
K_θ	Stiffness coefficient [unitless]
L	Flexure length [in]
ρ	Curvature coefficient[unitless]
θ	Final angle of flexure [degrees]
θ_i	Initial angle of flexure [degrees]
$\Delta\theta$	Degree of actuation [degrees]

DESIGN CRITERIA

In cooperation with surgeons at Boston Medical Center, requirements were determined for a novel laparoscopic grasper. Drawing upon insight from medical professionals, the conditions and constraints of laparoscopic surgery were defined. The weaknesses of current laparoscopic devices were identified through both surgeon input and instrument testing in a surgical simulation laboratory. From this process, a set of functional requirements was established.

1. **Pick up and move organ structures.** This is the primary objective of the device.

2. **Engage organs in multiple different manners.** By offering surgeons more grasping options than just "pinching," the device will widen surgical capability. Specifically, hand-like grasping will be possible.

3. **Fit through a 12mm trocar port**. This is a large diameter port available for laparoscopic surgery and was chosen to simplify the proof-of-concept fabrication process. Subsequent designs will be miniaturized for use with 8mm and 5mm ports.

4. **Operable by one hand.** Surgeons are often required to operate multiple laparoscopic instruments and can thus only dedicate one hand to the operation of a given device.

5. **Do no harm to patient.** Specifically, the device must be safe to use in conjunction with electro-surgical techniques and instruments.

6. **Be comfortable for a surgeon to operate.** Laparoscopic surgeries can last many hours. This device requires an ergonomic and intuitive hand interface, in addition to a low overall mass.

7. **Sterilizable.** The device must be compatible with a standard sterilization practice, such as autoclaving, ethylene oxide gas, or gamma irradiation.

8. **Priced appropriately.** Whether disposable or reusable, the device must be priced within the acceptable range of the corresponding product class.

With functional requirements determined, relevant parameters of the system were quantified. The organs likely to be grasped are the small and large intestine, with respective diameters of 1.0 and 2.4 in [2.5 and 6 cm], as well as the liver and the stomach, with a typical dimension on the order of 3.9 in [10cm] (2).

Current laparoscopic grasper geometries were also examined, as well as typical pinching forces. Studies have quantified the tissue perforation threshold as a function of grasper area and pinching force. Depending on pincher size, the threshold for tissue perforation ranges from 3.4-9.0 lbf [15-40 N] (3).

Next, typical laparoscopic device transmission ratios were examined. This ratio represents the relationship between the surgeon's manual input force and the grasping force. Prior investigations measuring typical transmission ratios provided a first order approximation of the frictional losses of the device. Typical transmission ratios range from 2 to 5 (input force/output force) (4).

Finally, a literature review offered insight into the typical forces and durations of a surgeon's grip on the laparoscopic device handle. A study of thirty surgeons performing two types of procedures reported that the mean and maximum gripping forces were 1.9 lbf and 15.3 lbf [8.52 N and 68.17 N], respectively. Furthermore, the mean and maximum gripping times were 2.29s and 66.27s respectively (5). While it was understood that this grasper would perform differently than current devices, these numbers helped to frame the design criteria.

DEVICE DESIGN

The design of the device was split into three modules: handle, transmission shaft, and end effector. Illustrated in Figure 2, the modules were engineered and prototyped independently.

Figure 2: Overall device structure. From left to right: handle, transmission shaft, and end effector.

The handle is the instrument's user interface and contains the control mechanisms for the device. The transmission shaft couples the handle and the end effector. The end effector engages the organs subject to manipulation. Following optimization, the three modules were integrated into a proof of concept prototype.

END EFFECTOR

The end effector is the most critical module of the laparoscopic device; its grasping capability differentiates this design from other devices currently on the market. One of the most pressing requirements is the need to grasp larger objects such as the stomach and bowels as opposed to smaller folds of tissue. Independent digits were designed to allow manipulation of these objects in a manner not possible with current laparoscopic instruments.

An initial consideration was the minimum number of digits required for the end effector. Human gripping patterns of irregular objects were analyzed along with the mathematical basis of grasping. To exactly constrain an object in a given plane, three points of contact are required. Such kinematic constraint is desired to efficiently grasp and manipulate.

Redundant designs, with more than three fingers allow for an increase in maneuverability and handling. However, overly complex control mechanisms are required in order to effectively actuate these motions. This device was designed to be operated by one hand, which led to a three fingered design. Symmetric patterning of the fingers was utilized for simplicity, as well as manufacturing economy. Additionally, this design allows for an adequately large gripping plane. With the end effector concept defined, actuation and flexing mechanisms were analyzed.

Both independent and coupled motions were considered for each finger. The objective of the end effector is to securely grip an organ and the most robust grip on an object occurs when the three points of contact best resist the applied forces and moments. However, objects with varied geometries require different grasping patterns to achieve the most secure grip. Independent actuation of the three fingers was considered to allow for an adjustable gripping plane. However, internal organs are extremely compliant and therefore the benefit from complex gripping schemes is marginal. Furthermore, independent finger actuation drastically increases the control handle complexity. As a result, in this prototype all three fingers of the end effector are co-actuated.

Multiple avenues were explored to enable finger articulation. Fingers with rigid segments connected by pin joints were considered, but were deemed overly complex. Underactuated fingers were investigated because they require just one input (6); however, such designs proved to be theoretically complex and difficult to miniaturize to the size required by the laparoscopic trocar. Flexural bearings presented themselves as a natural choice due to their flexibility in design, scalability, low error, and low part count (7).

The end effector consists of three, symmetric and identical monolithic fingers, each with three discrete flexural joints. The joints were modeled as initially curved pseudo-rigid-body elements (8). Using this model, the initial angle of curvature for each flexure was solved as Θ_i. A complete solution for this angle, as well as the pseudo rigid body model used can be found in (8).

Each finger consists of three discrete joints. The first joint, known as the base joint, was designed to accommodate 45 degrees of articulation, while the latter two joints are designed for 90 degrees of articulation. After determining the degree of articulation $\Delta\Theta$, the final flexural angle Θ, can be solved as

$$\Theta = \Theta_i + \Delta\Theta \qquad (1)$$

Next, the stiffness, K, of the flexure can be evaluated as

$$K = 2\rho K_\Theta \frac{EI}{L} \qquad (2)$$

where E is Young's Modulus, I the area moment of inertia, L the curvature length, and K_Θ and ρ the stiffness and curvature coefficients, respectively. These values are a function of the initial conditions of the flexure.

If stiffness is known, the force required to actuate the flexure, F, can be solved as

$$F = \frac{K(\Theta - \Theta_i)}{b} \quad (3)$$

where b is the height of the flexure.

Finally, maximum stress can be tuned against the yield stress of the flexure material to prevent yielding. The maximum stress in the flexure, σ_{max}, as a function of flexure thickness, t, can be solved as

$$\sigma_{\max} = \frac{Fbt}{2I} - \frac{F}{A} \quad (4)$$

Force applied from tensioned control cables is distributed between the three joints. The degree to which each joint articulates is dependent on its stiffness. This leads to a deterministic relationship between the applied force and the finger deflection. In designing the flexural joints, both absolute stiffness and relative stiffness to the accompanying joints were analyzed. Absolute stiffness of the joints dictates the force required for actuation. The relative stiffness of the three joints dictates the curling pattern of the finger during actuation.

The stiffness of the joints decreases from the base joint to the furthest joint. This results in a primary actuation at the furthest joint, secondary actuation of the middle joint and tertiary actuation of the base joint. Assuming a nominal value of stiffness for the base joint, K, the following two joints have stiffness of $\frac{2}{3}K$ and $\frac{1}{3}K$, as can be seen in Figure 3. This stiffness profile enables the finger to mimic the common gripping pattern of human fingers.

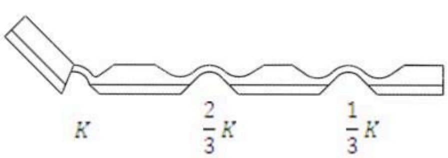

Figure 3: Relative joint stiffness in a finger.

Two modes of actuation were designed. First, a cable fixed at the finger tip and traversing through holes in the rigid finger segments actuates a "curling" of the finger. A second cable, attached to the base joint, allows isolated actuation of that joint only. This allows the fingers to "fold" to a small profile and fit through the trocar. Figures 4-6 demonstrate the initial and actuated finger positions.

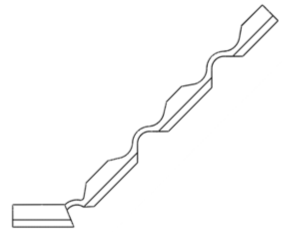

Figure 4: Finger at rest

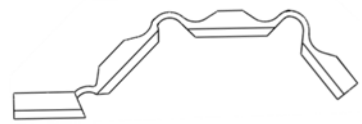

Figure 5: Finger curling

Figure 6: Finger folding

Three such fingers were patterned radially, creating a grasping plane orthogonal to the shaft axis. When open, each finger extends at a 45 degree angle from the transmission shaft. A complete diagram of the extended end effector appears in Figure 7.

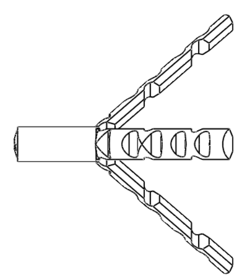

Figure 7: Complete end effector

The cross section of each finger is a modified one-third section of a circle. When folded, the three fingers form a structure with a circular cross section, capable of passing through the trocar, as illustrated in Figure 8.

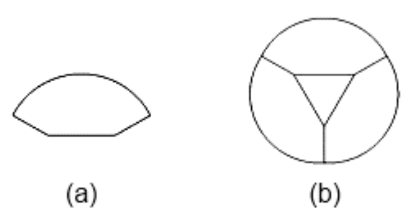

Figure 8: (a) Single finger cross section and (b) complete end effector cross section when folded

Prior to prototype fabrication, finite element analysis was performed on flexural joints of varying stiffness. This analysis was used to verify the stress analysis performed above and to confirm force-deflection expectations.

TRANSMISSION SHAFT

The transmission shaft connects the end effector and the handle while providing structural stiffness. This module was designed to fit through the trocar port and also be compatible with electrosurgical procedures. Additionally, the control cable clusters are housed within the transmission shaft. Made from nylon coated cable to reduce friction, these control cables connect the triggers and fingers. The three “folding” cables (one from each finger) are spliced into one cable, which travels the length of the transmission shaft and attaches with the trigger. A similar bridal is used to couple the three “curling” cables.

HANDLE

The handle is the user interface of the device; as such, it must be ergonomic, intuitive and accurate. A pistol grip design is used for its simplicity and robustness. Recent studies have shown that a pistol grip enables better control than a traditional scissor grip (9). However, unlike a standard pistol, this handle has two triggers. One trigger causes all fingers to “fold,” actuating only the base joint. The second trigger actuates the latter two finger joints, causing the fingers to “curl.” Each trigger causes the coordinated actuation of all three fingers.

The design of the handle can be broken into two elements: mechanics and ergonomics. The mechanical design involves the trigger, ratchet and lock mechanisms. The ergonomic design involves the geometry of the outer handle case, which interfaces with the surgeon's hand.

The primary internal mechanisms of the handle are the dual triggers. Positioned side by side, but offset vertically, these triggers allow the fingers to be actuated by a surgeon’s index and middle fingers. From the transmission shaft, the control cables are routed around pulleys and attached to the triggers. Each trigger is connected to the handle structure via an extension spring, which returns the trigger to its original state. The upper internal geometry of each trigger is circular, with ratcheting teeth. A constant radius allows the teeth to continuously contact the ratchet lock.

The ratchet locks engage and disengage with bi-stable toggle levers on the top of the handle. In the first stable state, the ratchet lock engages the ratchet teeth. In the second stable state, the ratchet lock is not in contact with the teeth. The stable states are separated by geometry and spring-induced potential energy peak. Applying firm force on the lever allows transition from one stable state to the other. The handle mechanism appears below in Figure 10.

Figure 10: Rendered internal mechanism of handle.

The ergonomics of the handle is addressed in the casing. Numerous studies have shown that laparoscopic surgeries result in increased risk of injury to the surgeon. The most common injury is digital neuropraxia, which is characterized by a numbness of the thumb (10-13). This is generally a result of excessive pressure caused by ring handled-instruments on the digital nerves.

The handle exterior fits ergonomically in a surgeon’s hand, with the index and middle finger engaging triggers, the thumb controlling the locking levers, and the ring and pinky fingers wrapped around the handle bottom. Geometric design was an iterative process, in which handles were modeled with clay and tested for comfort. The handle casing can be seen in Figure 11.

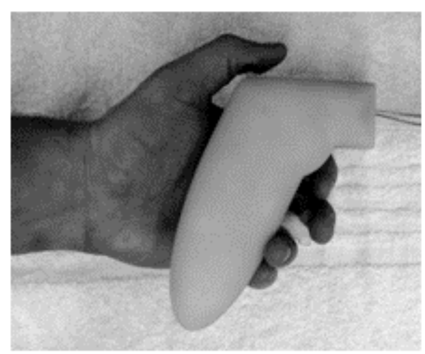

Figure 11: Exterior handle casing

The girth of the handle is sized for a nominal human hand. Sharp geometries and slope changes are minimized. Additionally, because the exterior case simply bolts to the handle structure, different sized cases can be attached for use by surgeons with different sized hands.

PROOF OF CONCEPT PROTOTYPE AND TESTING

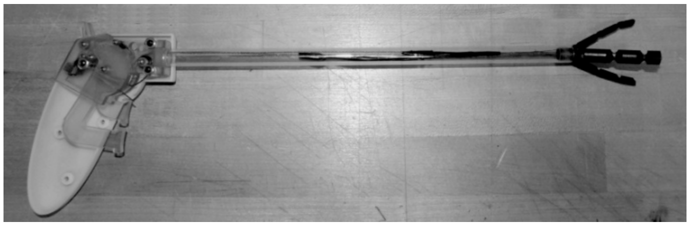

Figure 12: Full proof of concept prototype (note: upper handle casing removed).

Following the optimization and integration of all modules, a proof of concept prototype was fabricated, as shown above in Figure 12. The fingers were precision-milled from nylon. This material was chosen for its ease of manufacturability and economy. Dimensions of the proof of concept fingers are presented below in Figures 13 and 14.

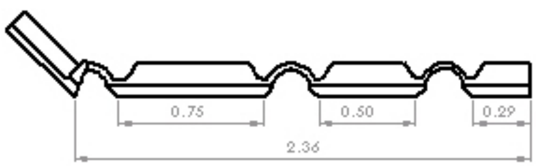

Figure 13: Proof of concept finger geometry (all dimensions in inches)

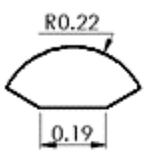

Figure 14: Proof of concept finger cross section (all dimensions in inches)

Fishing line runs through small bores in the fingers to actuate the flexural joints. The fishing line is attached to nylon-coated steel cable 0.040 inches in diameter, which traverses the transmission shaft and connects to the triggers.

The transmission shaft and internal mechanisms of the handle were created from polycarbonate structural tubing and sheet stock, respectively. The exterior handle casing was fabricated from nylon via a stereolithography process. The prototype device weighs 6.0 oz completely assembled.

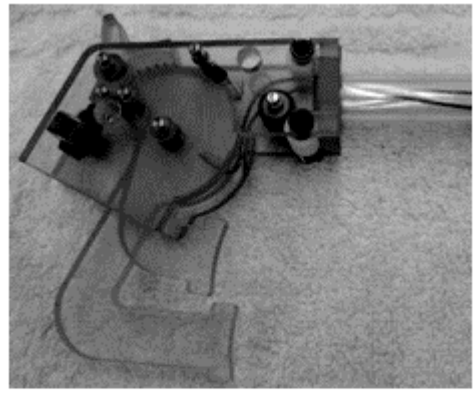

Figure 15: Prototyped internal handle mechanism

To validate the proof of concept prototype, a regime was designed to test the device's ability to achieve the established functional requirements. The primary objective of this prototype was to demonstrate the mechanics of the device. Therefore, the assembled device was subjected to the following testing regime:

1. Finger articulation in both fold and curl motions
2. Device insertion through 12mm trocar and end effector expansion once inserted
3. Retrieval and release of a 1.5 in [4 cm] diameter sphere
4. Retrieval and release of a 2.4 in diameter soft cylinder

Through the dual triggers, the end effector is able to articulate in both the fold and curl motions. As expected, the more compliant end joints articulate prior to the stiffer base joints. This proves that the pattern of finger articulation can be controlled by joint stiffness specification. The folding motion enables the end effector to fold into a circular cross section and fit through the 12mm trocar. However, a chamfer on the front face of the end effector would allow for easier insertion through the trocar.

Additionally, the curling method of articulation allows for grasping of curved surfaces. Curling is of particular importance when grasping smooth or slippery objects, as it allows for a more secure grip. This is demonstrated by the grasping of the smooth plastic sphere in Figure 16. Additionally, the ratcheting mechanism is capable of locking the end effector in the gripped position.

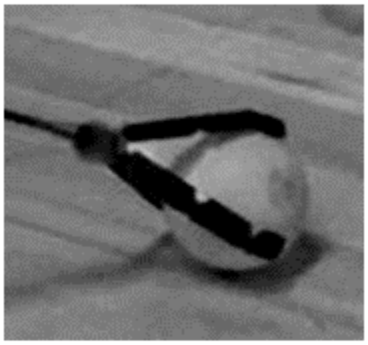

Figure 16: End effector grasping sphere

Testing revealed that the absolute values of joint stiffness are too high. Full articulation of both the curl and fold motions require an uncomfortable level of user force input. Because laparoscopic procedures are delicate operations, griping of the device should require minimal effort. Methods to mitigate the force input required will be considered in future iterations.

The importance of a textured gripping surface was also realized through testing. While the device is able to pick up smooth objects, a gripping surface with increased friction will enhance grasping stability.

Lastly, while comfortable, the handle casing is slightly large for a typical user. This makes single handed engagement and disengagement of the ratchet levers difficult for users with smaller hands.

Functional requirements not directly examined were pricing, sterilization, and patient safety. However, a preliminary materials and manufacturing analysis estimates the production cost at $25 per unit. Additionally, all components used in the development of the prototype are compatible with ethylene oxide sterilization or can be manufactured with compatible materials. During future materials selection, the device's ability to be sterilized will be further considered. Finally, there is no electrically conductive external component in the prototype, rendering it compatible with electrosurgery. A more complete assessment of patient safety will be conducted in further iterations. The current design has numerous aspects that must be refined to meet patient compatibility standards. For example, the fingers will be sheathed to cover the control cables as well as the flexure crevice

DISCUSSION AND FUTURE ITERATIONS

This prototype demonstrates the mechanics of a flexural laparoscopic grasper. Testing validated certain aspects of the design, while offering key insights for future revisions. The symmetric, three fingered end effector exhibits enhanced grasping capability when compared to traditional "pinching" end effectors. The finger's ability to curl around objects allows for grasping via geometric constraint and not solely pinching force. As a result, it is predicted that this design will result in minimal tissue perforation. Additionally, the dual trigger design is an intuitive and accurate user interface.

Both the design process and the testing regime illustrated aspects of the device that can be improved. As detailed below, enacting these changes will elevate the device from a proof of concept to a beta prototype.

Joint Stiffness and Fatigue

Because fingers with flexural joints have a low part count and are highly customizable, this design will be continued in future iterations. However, both the absolute and relative values of joint stiffness will be further examined. Less stiff joints are desired to minimize the required user input force. However, the flexures must be sized to prevent yielding and ensure complete spring back. More in depth stress analysis will be completed using Castigliano's method and used to appropriately size the next generation of flexural fingers. A more rigorous model will be created to predict finger tip displacement as a function of control cable tension. Furthermore, finger tip deflection as a result of resultant gripping forces will be examined. Through this model, the variance of the stiffness between the three flexural joints will be adjusted to optimize the finger design.

A fatigue analysis will be performed on the flexure joints. The joints must withstand multiple articulation cycles and fatigue will be considered as final materials selection is performed.

Finger Design and Scaling

The fundamental design of the fingers will be maintained, including the finger size and respective lengths of the segments. However, a chamfer will be added on the front face of the finger tip. This should allow for easier insertion of the device into a trocar.

With the mechanics proven on a device that fits through a 12mm trocar, the device will be scaled for use with smaller ports, such as 5mm and 8mm trocars. Smaller devices are advantageous because they require smaller incisions. However, the 12mm port device has the capability of engaging larger organ structures. It is anticipated that a range of available devices will provide surgeons with the most complete grasping capability.

Finger Sheath

A sheath covering will be designed to encapsulate the flexural fingers. This flexible membrane will be made from biocompatible materials and prevent the flexural joints and control cables from becoming entangled with internal organs. This casing may incorporate textured gripping pads on the inner portions of the fingers. Such a sheath may assist in making the device adequately sterilizable. Ideally, the finger structures would be re-usable and sterilizable, while the outer sheath is disposable. The specific engineering challenges of this sheath will be material selection and the mechanism that secures it to the grasper.

Independent Finger Actuation and Asymmetric Design
The prototype described here can easily be adapted to allow independent actuation of each finger. Cables from each finger will be run through a multilumen transmission shaft and actuated separately. The cable actuation method described here can allow for the articulation of each individual joint on a finger, providing control of up to nine degrees of freedom for a three fingered end effector.

In addition, there are a number of possibilities available for the spatial layout of the fingers apart from rotational symmetry. Asymmetric designs will be considered further in tandem with a novel control mechanism.

Wrist and Shaft Rotation Capability
A wrist like degree of freedom is desired for the device. This motion would allow the end effector to reach around internal objects, enhancing grasping capability. Additionally, wrist articulation will allow for grasping in a plane orthogonal to the trocar. This may allow for clearer observation through the laparoscopic endoscope.

Therefore, a more refined solution will be developed to enable wrist articulation. A simple solution would be the inclusion of a hinge connecting the end effector to the transmission shaft and allowing one rotational degree of freedom. By combining rotation about this hinge with rotation of the device about the longitude transmission shaft axis, compound wrist articulation will be possible.

To allow transmission shaft rotation, the control cables must be de-coupled from the shaft to prevent tangling. This may be accomplished with the use of a component with a freely rotating part, similar to a bearing. The exterior of this component can be unconstrained axially along the transmission shaft, but constrained rotationally with a keyway. The control cables are connected to the inner rotational component of the bearing. This effectively isolates the control cables from rotational shaft movement. When the trigger is actuated, cable tension moves the bearing unit axially, thereby causing finger articulation.

Handle Casing
The ergonomics of the handle will be reevaluated and the overall size of the handle will likely decrease. It is important that the handle allow for single handed operation of the triggers and the ratchets.

Additionally, while the current dual triggers are offset out of plane, they will be relocated in plane. This will suppress any difference in user grip when the handle is held with the right or left hand. Additionally, a dotted, Braille-like texture may be added to one of the triggers and its corresponding lock lever. This will enable a surgeon to differentiate between the triggers through tactile feel. Lastly, while extension springs were used to return the triggers in the proof of concept device, future iterations will use torsion springs.

Force Sensing Mechanism
To regulate the force transmitted by the end effector, controlled compliance could be added within the transmission cables that would be activated when a specific tension is reached. This could be achieved by a tension spring with adjustable pretension that is relative to the desired maximum end effector force. The tension spring would be fixed to a linear slide through which the transmission cable would be routed. A pulley would be used to reduce the friction within the connection.

Materials Selection and Manufacturing
The materials used for the proof of concept prototype were chosen largely for ease of manufacturing. In the next phase of the device development, biocompatible materials will be selected and a final sterilization technique chosen. Plastics such as low-density polyethylene (LDPE) and medical grade polyurethanes are being considered. Following with a detailed stress analysis, an appropriate material will be selected for the flexural fingers. Ideally, these fingers will be manufactured via an injection molding process because of their complex geometry. The variation in wall thickness of the finger may need to be reduced to make injection molding feasible.

The handle design will also be adjusted to be manufactured via injection molding. Additionally, the internal mechanism and exterior casing components of the handle will be integrated to minimize part count. By utilizing economical injection molding processes, the cost of manufacturing will be minimized.

CONCLUSION
A three fingered laparoscopic grasper was developed to enhance surgical gripping capability. The symmetrical design has two modes of actuation, allowing the end effector to engage organs in multiple complex manners. Moreover, the end effector widely distributes the gripping force, which will help to prevent organ tissue perforation. Finally, the device is capable of inserting through a standard laparoscopic trocar port.

Flexural joints were utilized to enable finger articulation, which allows for a low part count and highly customizable appendages. The flexures were modeled as pseudo-rigid-bodies and the geometries were validated through finite element analysis.

This proof of concept device demonstrates the mechanics behind a flexural laparoscopic grasper. Continued device development will focus on optimizing flexure geometry, materials selection, and product packaging.

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REFERENCES

[1] Heijnsdik, E., Dankelman, J., Gouma, D.J., 2002, "Effectiveness of grasping and duration of clamping using laparoscopic graspers," *Surgical Endoscopy*, 16, pp. 1329-1331.

[2] Thibodeau, G., Patton, K., 2009, *Anatomy & Physiology 7th ed.* Mosby, St. Louis, Missouri.

[3] Heijnsdik, E., Dankelman, J., Gouma, D.J., 2004, "Slip and damage properties of jaws of laparoscopic graspers," *Surgical Endoscopy*, 18, pp.974-979.

[4] Westebring-van der Putten, E., et al, 2009, "Effect of laparoscopic grasper force transmission ratio on grasp control," *Surgical Endoscopy*, 23, pp. 818-824.

[5] Brown, J.D. et al., 2004, "Quantifying Surgeon Grasping Mechanics in Laparoscopy Using the Blue DRAGON system," *Studies in Health Technology and Informatics*, 98, pp.34-36.

[6] Steutel, P., Kragten, G., Herder, J., 2010, "Design of an Underactuated Finger with a Monolithic Structure and Largely Distributed Compliance," DETC2010-28, *Proceedings of the ASME 2010 International Design Engineering Technical Conference & Computers and Information in Engineering Conference*, Montreal, Quebec, Canada.

[7] Lotti, F., Vassura, G., 2002, "A Novel Approach to Mechanical Design of Articulated Fingers for Robotic Hand," *Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems, Lausanne, Switzerland,* pp. 1687-1692.

[8] Howell, L., 2001, *Compliant Mechanisms,* Wiley, New York.

[9] Büchel, D., Marvik, R., Hallabrin, B., Matern, U., 2010, "Ergonomics of disposable handles for minimally invasive surgery," *Surgical Endoscopy*, 24, pp. 992–1004.

[10] Horgan, L.F., O'Riordan, D.C., Doctor, N., 1997 "Neurapraxia following laparoscopic procedures: an occupational hazard," *Minimally Invasive Therapy and Allied Technologies*, 6, pp. 33–35.

[11] Kan,o N., Kasugai, H., Yamakawa, T., 1993, "Laparoscopic surgeon's thumb," *Archives of Surgery*, 128, p. 1172

[12] Majeed, A.W., Jacob, G., Reed, M.W., Johnson, A.G., 1993, "Laparoscopist's thumb: an occupational hazard?," *Archives of Surgery*, 128, p. 357.

[13] Van der Zee, D.C., Bax, N.M.A., 1995, "Digital nerve compression due to laparoscopic surgery," *Surgical Endoscopy*, 9 p. 740