

Flexible Support Scaffold for Organ Retraction in Laparoscopic Surgery

by

Adam D Sachs

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

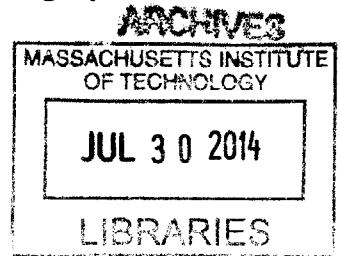
Bachelor of Science in Engineering, as Recommended by the Department of Mechanical
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Signature redacted

Signature of Author
Department of Mechanical Engineering
December 16, 2013

Signature redacted

Certified by
Alexander Slocum
Neil and Jane Pappalardo Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Accepted by
Anette Hosoi
Undergraduate Officer

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Abstract

With millions of abdominal surgeries performed annually in the United States alone, abdominal surgery is both a large market and a large medial issue. The entire industry surrounding abdominal surgery has strived to reduce the pain and trauma associated with an operation by reducing the number and size of incisions made in the abdominal wall, but in the process of reducing openings into the abdomen, the difficulty of operating increases.

In order to retract organs within the abdominal cavity while further reducing the number of ports required for surgery, the author has previously designed and fabricated a device to be inserted into the abdominal cavity through one small port. Once inside of the abdominal cavity, the device expands to form a rigid platform across the ventral abdominal wall serving as a platform for organ retraction. While the previously fabricated device functions as intended, its rigid shape does not match the shape of the ventral abdominal wall, and as such, the device occupies unnecessary operating space.

The work of this paper involves the design of a system to permit the existing device to conform to the shape of the ventral abdominal wall while still supporting a load. Two methods were examined to permit the device to conform while still supporting a load: Flexure and Hinged joints. Both flexure and hinged joints were developed, prototyped, and analyzed to meet all functional requirements. Both methods proved ultimately successful in meeting functional requirements, yet flexure joints were significantly easier to produce and thus represent a more viable solution for mass production.

Thesis Supervisor: Alexander Slocum

Title: Neil and Jane Pappalardo Professor of Mechanical Engineering

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1. Introduction and Background:

Over two million laparoscopic surgeries are performed annually in the United States.¹ Over the past twenty-five years, a strong push has been made to minimize the size and number of incisions required to perform such a surgery, and this push has led to the prevalence of laparoscopic surgery: performing surgery using a camera and instruments through a few small incisions.

1.1 Opportunity

During laparoscopic abdominal surgery, a surgeon makes a few small incisions in the abdominal wall and inserts a device called a trocar – a small tube that is inserted into the incision through which instruments can easily pass. The abdomen is then inflated to give the surgeon an area in which to work, and the trocar retains the gas with a rubber check valve. Yet even with the distended abdominal cavity, it can still be difficult to work on a single organ. This difficulty is due to the number of organs loosely retained in the relatively small space of the abdominal cavity. To mitigate this problem, a surgeon typically will work with a Physician Assistant whose primary job will be to hold the camera and lights as well as to retract organs. This results in two people operating in the same small workspace, frequently with arms intertwined to allow proper working angle and visualization of the surgical field. As a result of the careful choreography required for two people to work on one patient's abdomen, a surgeon and assistant will frequently pair up and work together for years once accustomed to each other's movements.

This difficulty in visualizing the surgical field as well as difficulty maneuvering within the abdomen can be observed in Figure 1 where the liver is obstructing visualization and movement around the operating field during an operation on the patient's stomach. This constant obstruction of the operating field not only demands that a surgical team be well coordinated and rehearsed, but additionally results in longer surgeries with an increased chance of complication including damage to the surrounding organs or anesthesia related problems.

¹ "FDA permits marketing of a new device for abdominal surgery" *U.S. Food and Drug Administration*. n.p. 1 May 2012. Web. 9 September 2013.



Figure 1: Image of a patient's abdominal cavity during laparoscopic surgery. The lighter pink organ in the bottom of the image is the patient's stomach (the organ being operated on). The darker red organ in the top of the image is the patient's liver. The surgical tool in the bottom center of the image is a laparoscopic stapler. Image source: Dr. Barry Greene.

1.2 Existing Solutions

Problems resulting from obstructing the surgical field are a well known in abdominal surgery. Over decades, numerous solutions have been developed for open (non-laparoscopic) operations, many in the form of organ retraction tools. Despite the plethora of solutions for organ retraction in open surgery, the problem of laparoscopic organ retraction is for the most part unsolved.

One interesting solution to the problem of laparoscopic organ retraction involves the use of magnets to suspend an organ against the ventral abdominal wall without any incision through the wall (see Figure 2). While this technique is promising for some patients, for many patents this technique cannot be used as excess abdominal adipose tissue prevents proper magnetic adhesion.



Figure 2: Image displaying an organ suspended by a chain of magnets with no puncture of the abdominal wall.²

2. Previous Work

Prior to work specifically for this thesis, a significant amount of research was conducted by the author on the concept of a folding scaffold to support organs within the abdomen. In 2009, Doctor Barry Greene originally proposed the concept for a tool to support organs that could be collapsed and inserted via a trocar. This tool is to be a simple collapsing instrument that is inserted into the abdomen in a collapsed configuration. Once inserted, the instrument is expanded and attached to the dorsal abdominal wall. Once attached to the abdominal wall, this instrument can be used to support organs by suspending the organ above in instrument in a similar function to the magnetic retractor described in Section 1.1. Additionally, the instrument can be used to retract organs by attaching organs to the suspended instrument using clips or ties.

2.1 Previous Design

Over the past two years, two prototypes have been designed and fabricated following the design summarized in Section 2. Each prototype consists of five straight and rigid members attached with hinges. These members are capable of collapsing to be inserted through a trocar and expanded to support organs.

² <http://www.pediatricdeviceconsortium.org/devices/magic-retractor>

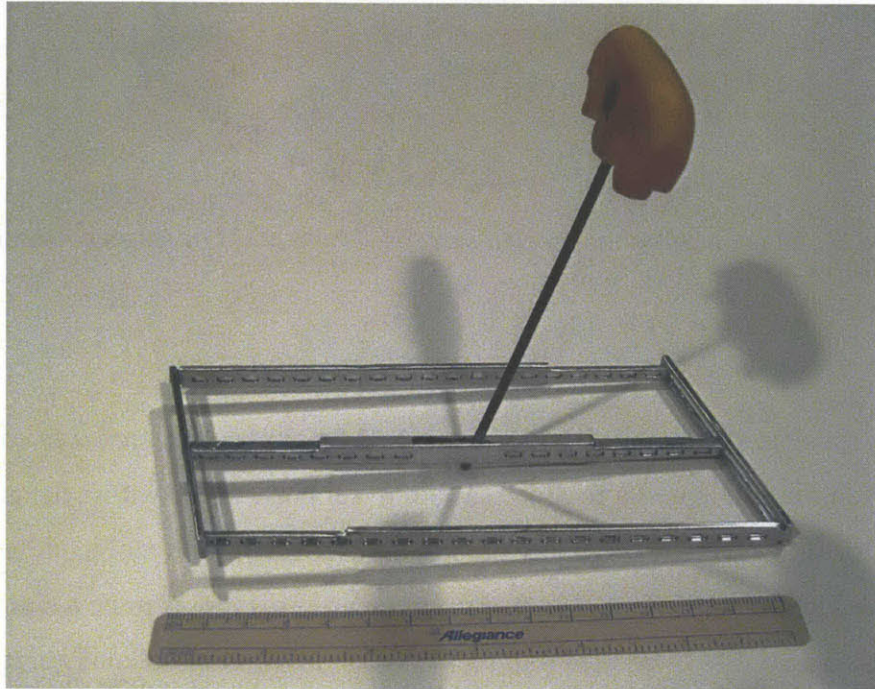


Figure 3: Image of a previously prototyped design. Note the vertical rod inserts through the ventral abdominal wall and serves to suspend the device.

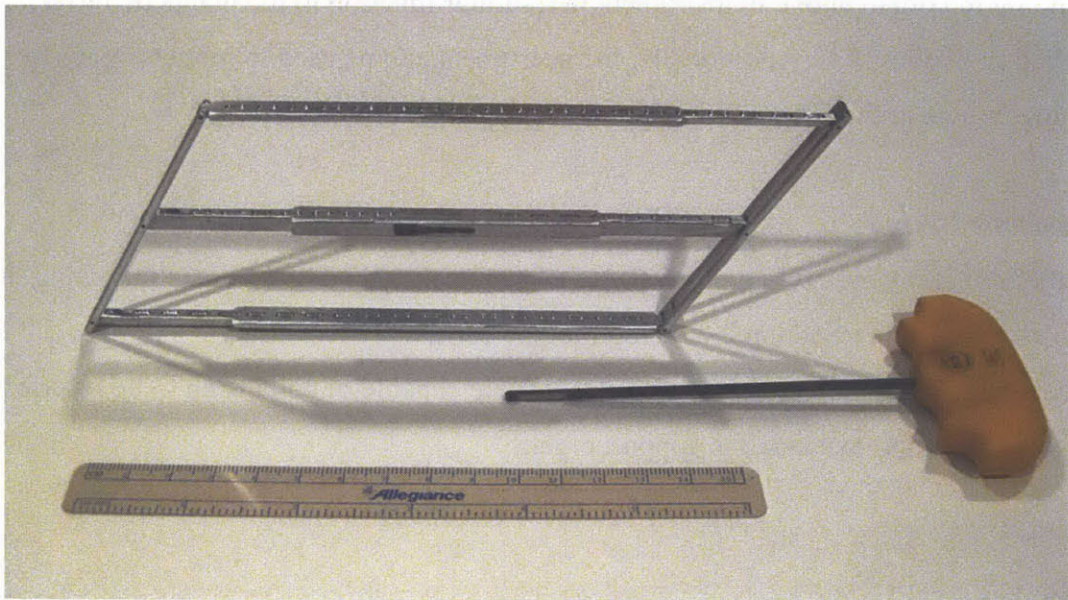


Figure 4: Image of a previously prototyped design in disassembled state.

2.2 Mismatch between Abdominal Wall Shape and Straight Scaffold

As described in section 1.1, during abdominal laparoscopic surgery the patient's abdomen is inflated with CO₂ in order to provide an area for the surgeon to operate within. This inflation results in the abdominal wall forming a dome shape above the abdominal cavity. When the existing scaffold device as described in Section 2.1 is inserted into the patient's abdomen, the device does not conform to the shape of the abdominal wall. This results in a large space between the abdominal wall and the device, which consumes a significant amount of the available room within the abdomen and results in reduced operating field area for the surgeon.

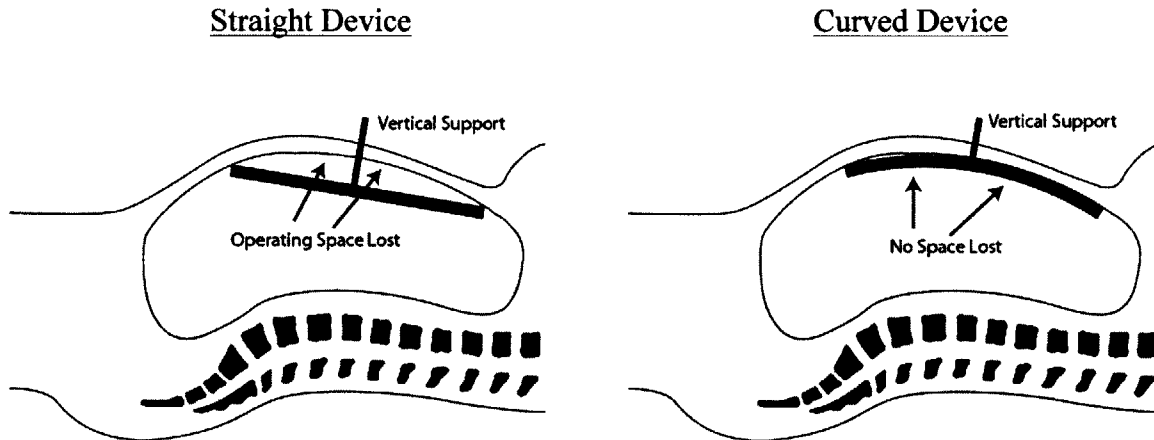


Figure 5: Left: Cross section of patient showing the mismatch between a patient's inflated abdominal cavity and a straight and rigid device. Note that the rigid device does not seat against the patients curved abdominal wall. Right: Diagram showing a curved and flexible device. Note that the device conforms to the shape of the abdominal wall resulting in minimal loss of operating space within the abdomen. Tracing from original image found at <http://www.thinkstockphotos.com/image/stock-illustration-cross-section-biomedical-illustration/150955033>

3. Current Work

It was decided that the scope of this thesis would encompass a solution to the problem of a rigid device not conforming to the shape of the patient's abdomen as described in section 2.2.

3.1 Flexibility Requirement.

As described in section 2.2, a curved device is required to properly seat against the patient's inflated ventral abdominal wall. Yet as the device must pass through a 12mm trocar (typical inner diameter of approximately 12-13mm, with length of 100-150mm), the device must be inserted while straight and curve once inserted into the abdomen. At the conclusion of the surgery, the device must be straightened so it can be removed via the same 12mm trocar.

To aid in simple insertion and removal, the device must not only be able to transition between curved and straight orientations, but must also spring into the straightened state when not loaded. This ensures that a surgeon could always remove the device quickly if required and would still allow the device to be placed quickly as the curved shape would form when loaded against the abdominal wall.

This thesis investigated four device designs to allow for flexibility. These designs are shown in Figure 6 and discussed in detail in Sections 3.2 and 3.3.

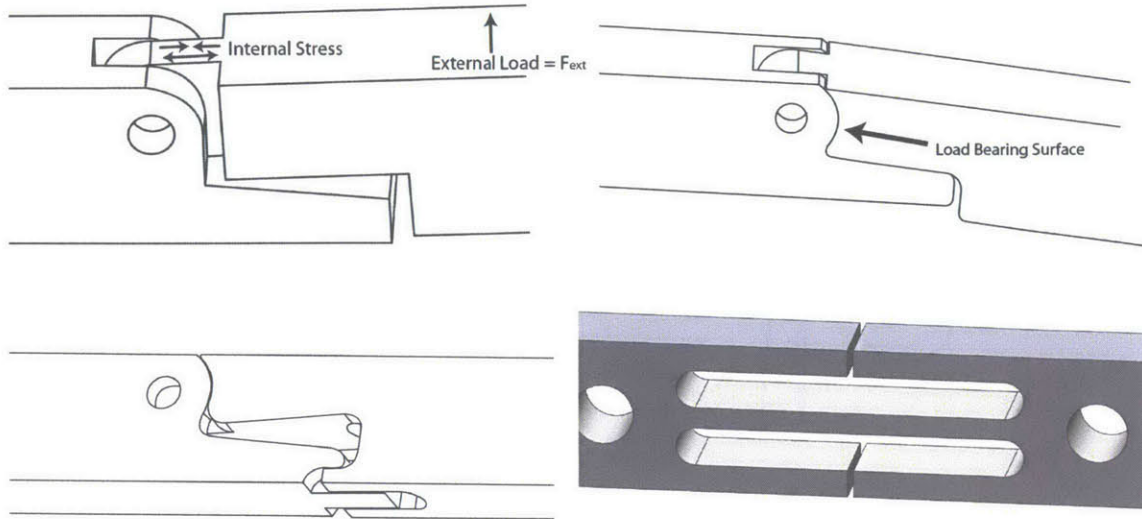


Figure 6: Image displaying the flexible joint designs investigated. From top left to bottom right Hinged Version 1, Hinged version 2, Hinged Version 3, Flexible Version.

3.2 Hinged Design Concept

In order to fulfill the requirements for a device that inserts into the abdomen while straight and conforms to the shape of the abdomen, a hinged rail was designed and prototyped. This rail consists of multiple “chain-link” type segments, which connect to form one single rail.

3.2.1 Hinged Version 1

The initial design consisted of four 2-inch segments to connect and form a single member at approximately 8 inches in length. Each hinged link would accommodate for a curvature of 5 degrees per link for a total curvature of 15 degrees across the 8-inch member.

When analyzed for resistance to torsional loading (see Appendix), it was determined that Hinged Version 1 when fabricated from aluminum would not have sufficient resistance to loads in the anatomically lateral direction. Such loads would reasonably be exerted when the device is suspended from its center and loaded laterally (see Figure 7). After determining this design would not have sufficient strength for typical use, the design was not prototyped.

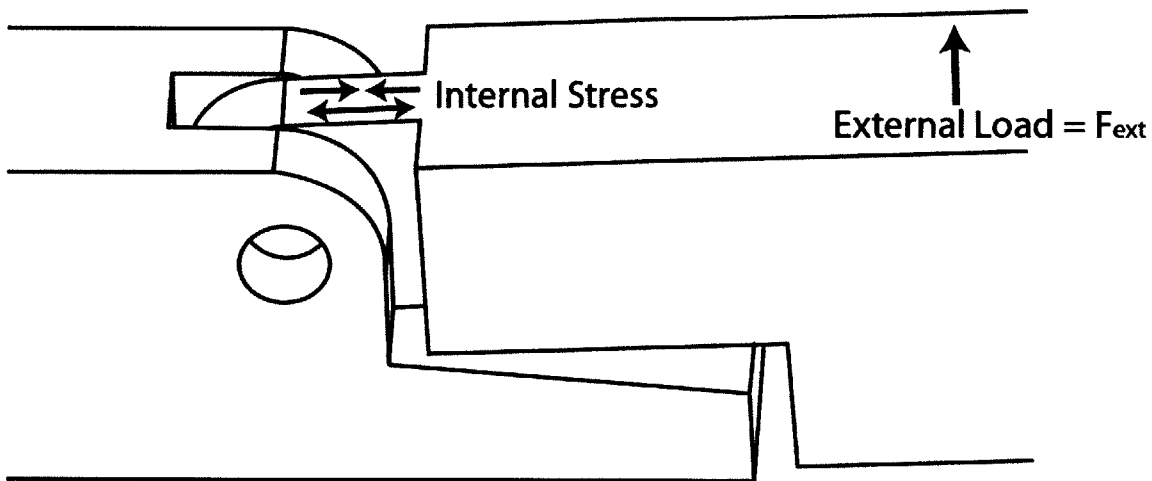


Figure 7: Diagram showing lateral loading of Hinged Version 1 and the resulting internal stress. Isometric view.

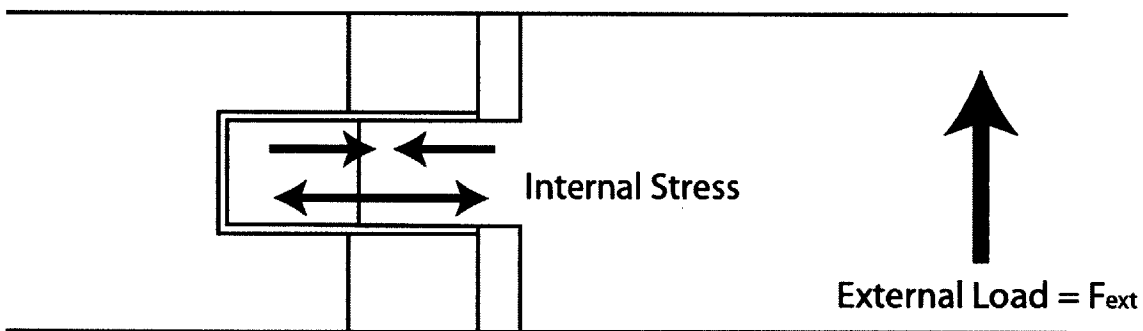


Figure 8: Diagram showing lateral loading of Hinged Version 1 and the resulting internal stress. Top view.

3.2.2 Hinged Version 2

After determining that Hinged Version 1 would have low resistance to lateral loads as subjected during normal use, the design was revised to adjust the forces along the hinge. Originally, in Hinged Version 1, a lateral load subjected a thin member to beam bending resulting in plastic deformation. To counter a typical lateral load, the hinge was designed to allow the member in the center to be under an almost purely tensile load while one

side-element is under compressive load (see Figure 10). This change does not significantly complicate manufacturing of the parts, yet is able to significantly increase the distribution of a lateral load across the joint. Thus, from an engineering standpoint, Hinged Version 2 is objectively a better design.

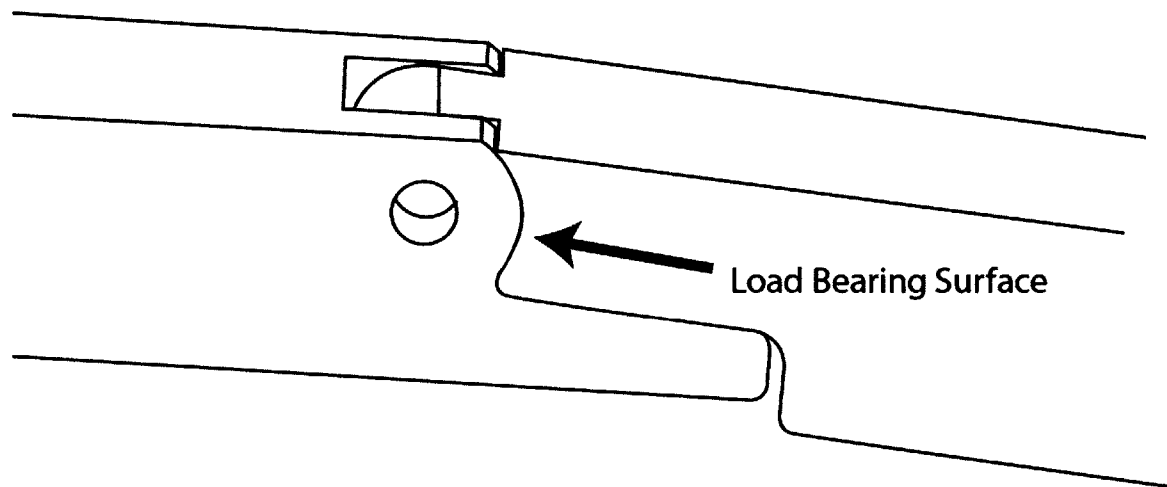


Figure 9: Diagram showing Hinged Version 2 with the inclusion of a load-bearing surface to support lateral loading. Isometric view.

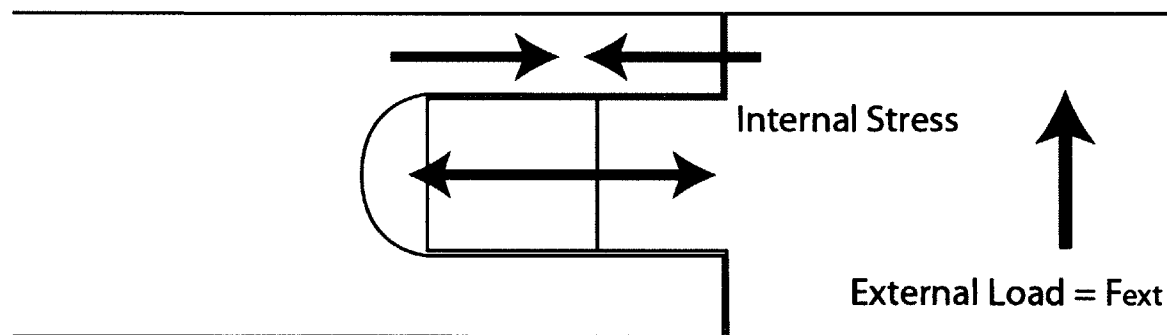


Figure 10: Diagram showing lateral loading of Hinged Version 2 and the resulting internal stress. Top view. Note that the internal stress is distributed over a large area as compared with Hinged Version 1 (**Figure 8**).

Hinged version 2 was initially prototyped using a Dimension 3D printer to produce the individual elements. These elements were connected using a pin to simulate a single rail's unfolding motion and static performance (Figure 11). This prototype was used to examine the “feel” of the system when manipulated by hand and to assist in an understanding of the ease with which this device would be inserted and removed from the abdominal cavity via a 12mm trocar.



Figure 11: Prototype of Hinged Version 2 produced using a Dimension brand 3D printer.

After examination of the 3D printed prototype, it was determined that while the 3D printed version did aid in gaining a more complete understanding of the device as well as its dynamics outside and within the body, an aluminum prototype would be required to more fully understand the design and to improve on its function. Additionally, the 3D printed model did not reveal any significant problems with the design of Hinged Version 2, although it should be noted that any detailed dynamics and rigidity could not be determined due to the inadequate resolution, tolerance, and quality of very small (less than 1mm) 3D printed parts. Components of the hinge itself could not be accurately replicated with a Dimension 3D printer.

As previously discussed, following the fabrication of a 3D printed prototype, an aluminum prototype was created from 6061 aluminum. This prototype contained only 3 links and was intended only to allow improved hinge design. These links were connected using carbon steel dowel pins.



Figure 12: Prototype of Hinged Version 2 produced from 6061 Aluminum using CNC milling processes. Individual segments are pinned together with a carbon steel dowel pin for prototyping purposes.

Overall, the aluminum prototype of Hinged Version 2 appears to have considerable promise for delivering the requirements of ability to conform to the abdominal shape, as well as rigidity and structural requirements. While the overall function of Hinged Version 2 is promising, the device itself had a few substantial flaws as outlined below:

Hinged Version 2 Rigidity

After prototyping, it was noted that Hinged Version 2 has a substantial amount of “wobble” within the hinged joints. This is likely due to inadequate tolerances maintained between the hinged parts in combination with a small distance between the hinge surfaces. This combination of factors allows the hinge to wiggle a total of approximately 4 per joint, allowing for a total of 12 degrees across the three joints. This would allow for a tip deflection of approximately 0.2 inches across a theoretical four-segment device resulting almost entirely from tolerance within the hinge without any deformation (elastic or plastic) of the aluminum or steel comprising the part.

In order to better understand the required dimensional tolerance of this design, a first order model was created to predict angular freedom due to joint tolerances. This model uses the arctangent function to calculate expected angular deflection based on given hole or pin tolerance (assuming no material deformation, plastic or elastic).

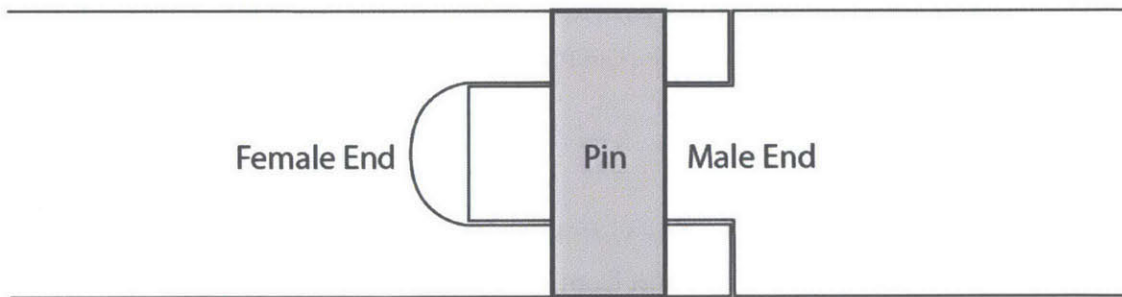


Figure 13: Diagram showing the pin within the joint of Hinged Version 2

Calculated Angular Deflection:

Hole Dia. minus Pin Dia. (inches)	Male End Angular Freedom	Female End Angular Freedom	Total Angular Freedom
0.0005	1.91	0.38	2.29
0.001	3.82	0.76	4.58
0.003	11.42	2.29	13.71

Table 1: Table of calculated angular freedom values given hinge diametrical tolerance for Hinged Version 2.

It is important to note that the designed diametrical clearance for the pin joint of Hinged Version 2 was 0.0005 inches along the female end of the joint and no clearance at the male end of the joint to allow free hinged movement. With the nominal designed clearance, the hinge would allow for wiggle of approximately 0.38 degrees per joint. As this table shows, a clearance of just under 0.001 inches on the male end of the joint would result in the measured 4 degrees of wiggle in the joint. In a mass production scenario, it would be difficult to control the total diametric clearance to always be under 0.001 inches.

Hinged Version 2 Resistance to Lateral Loading

While still maintaining a significant improvement over Hinged Version 1, Hinged Version 2 has only moderate resistance to lateral loads. A relatively small moment arm limits this strength across the hinge joint (see Figure 10).

Hinged Version 2 Range of Motion

Hinged Version 2 has a significant range of motion beyond the required range. Under normal function, the rail should transition from straight (during insertion and removal) to curved at a specified rate of curvature while in the abdomen. Hinged Version 2 fulfills the specified rate of curvature when inserted, but has no function to limit range of motion past straight. This would make it quite difficult to remove the device from the abdomen, especially in the fully assembled device where 3 identical rails are placed in parallel.

Manually straightening each rail would be nearly impossible preventing the device from being removed from the abdomen.



Figure 14: Image of Hinged Version 2 extended past linear. This hyperextension serves no purpose and would likely make insertion and removal from the abdomen challenging.

3.2.3 Hinged Version 3

Following the prototyping and analysis of Hinged Version 2, significant design changes were made to the design of the hinge in order to remedy the design inadequacies discovered in Hinged Version 2. In order to substantially increase the resistance to lateral loading as well as the rigidity of the hinged joint, an additional interlocking segment was added to the hinge. This segment increases the distance between locking joints thus decreasing the effect that stacked tolerance has on “wobble” between the joints (see Figure 16). The same model used to predict lateral freedom in Hinged Version 2 was used to predict lateral freedom in Hinged Version 3. Using this model, it was determined that 0.001 inches of clearance between parts would result in under 0.25 degrees of lateral freedom within the joint. This is in contrast to over 4 degrees of lateral freedom resulting from 0.001 inches of clearance in Hinged Version 2. With a clearance of 0.002 inches, Hinged Version 3 can still maintain an acceptable lateral freedom of under 0.5 degrees per joint.

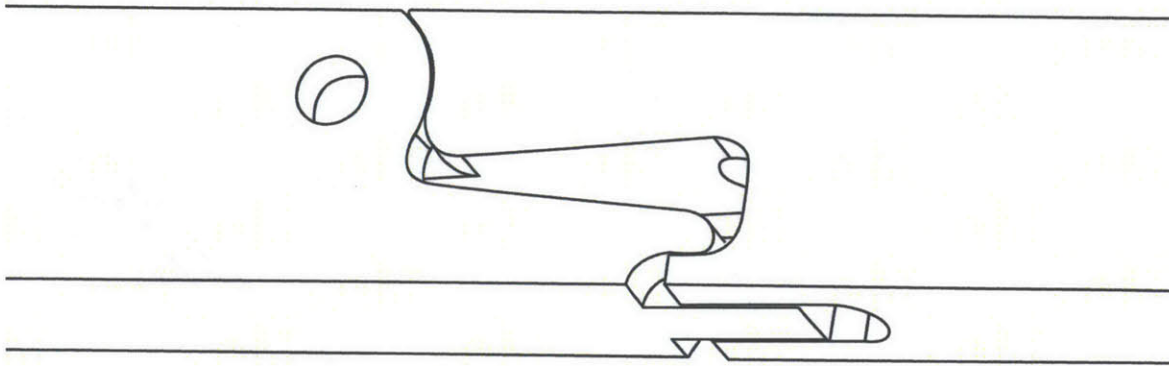


Figure 15: Diagram of Hinged Version 3. Isometric View.



Figure 16: Images showing Hinged Version 3 interlocking tab to prevent “wobble” laterally. Isometric View.

In addition to the substantially decrease wiggle between hinged joints, a small interlocking segment was added to the hinged design in order to prevent the rail from extending past linear (see Figure 17). This prevention of over-extending the device serves to aid in the removal of the device from the abdomen. Combined with an internal leaf spring to force the segments to return to a linear orientation when unloaded, Hinged Version 3 conforms to the shape of the abdominal wall when pulled upward against the abdomen and springs to a straight shape when released. These features make insertion and removal from the abdomen substantially easier as there is no need for the surgeon to straighten each individual link.

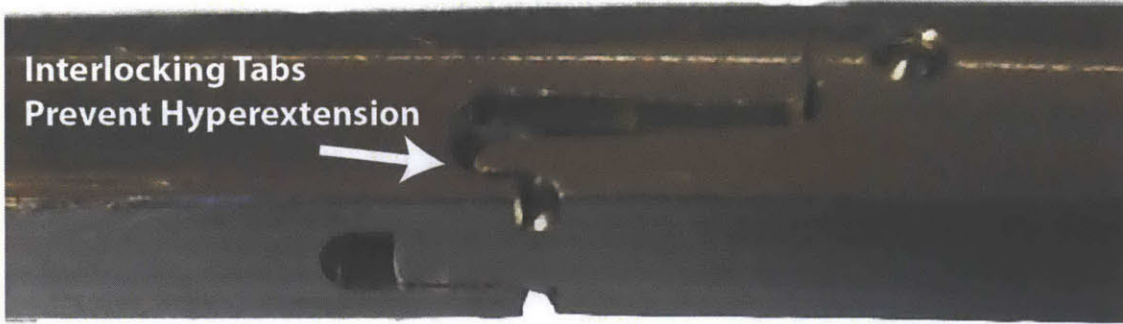


Figure 17: Image displaying the interlocking connection on Hinged Version 3 preventing extension past linear.

Overall, the function of Hinged Version 3 meets all requirements, yet the manufacture of the segments as well as the assembly of segments is very labor intensive. Each section of the rail is produced using numerous CNC milling operations machining four sides of the part. Additionally, the parts must be carefully aligned and pinned while encapsulating the leaf spring within. This process would be quite costly in mass production.

3.3 Flexure Design Concept

In order to meet the flexibility requirement outlined in section 3.1 while maintaining a design that would be practical and cost-effective to manufacture, a rail was designed and prototyped replacing the hinges with a metal flexure. The basic concept involves utilizing elastic deformation of the device structure to achieve the required flexibility without a multi-part hinge. Advantages of this design include ease of manufacture as well as minimizing the assembly required.

3.3.1 Material Selection

Many factors are involved in the selection of a material for a structural flexure. This list of requirements is further lengthened by requirements of biocompatibility for any device entering the human body.

For the flexure to function without plastic deformation, it must have a high ratio of yield strength to elastic modulus. An increased ratio would permit maximum strain before yielding, thus allowing the device to conform to the shape of the abdomen without

permanent bending. Additionally, to perform to structural requirements and suspend organs without deformation, the device would need to be fabricated from a material with relatively high modulus and high yield strength; this requirement likely excludes plastics from use as the primary structural member of this device, but to be sure, an analytical model was created as detailed below.

3.3.1.1 Material Selection: Plastic

Device fabrication from plastic using a standard injection molding process would significantly lower the manufacturing cost as compared with fabrication from stainless steel. With manufacturing cost in mind, plastic was analyzed as a potential device construction material as shown in the model below. This model simplifies the design to the extreme of a solid plastic bar with dimensions congruent with the functional requirements of a folding scaffold (fit through a trocar, multiple members, etc). This model was created with the understanding that if a solid bar of plastic cannot of the maximum allowable size cannot support the required load, it would be impossible to design a flexure entirely from plastic to support the same load.

The model was created with generally loose requirements as outlined below to aid in the "extreme" example.

- Dimensions must be 0.125 inches wide (patient medial-lateral) and 0.25 inches tall (patient anterior-posterior) in order allow 3 adjacent members to fit through a "12 mm" trocar.
- Must support a load of 15 N at the end of the bar while fixed at the center of the 8-inch length bar. This load simulates a liver of average mass³ supported by the device as intended during normal use.
- Must support the load without deforming significantly such that the device is not able to meet the functional requirement of supporting a load within the abdomen.

³ Elert, Glenn. "Mass of a Human Liver." *Hyper Text Book*. n.p. n.d. Web. 8 September, 2013.

Deflection Calculation

$$\text{Beam Width } w = 0.00318 \text{ m (0.125 in)} \quad (1)$$

$$\text{Beam Thickness } t = 0.00635 \text{ m (0.25 in)} \quad (2)$$

$$\text{Beam Length } L = 0.1016 \text{ m (4 in)} \quad (3)$$

$$\text{Modulus of Polycarbonate}^4 \quad E = 2.6 \text{ GPa} \quad (4)$$

$$\text{Beam Moment of Inertia } I = \frac{wh^3}{12} \quad (5)$$

$$\delta = \frac{PL^3}{3EI} \quad (6)$$

$$\delta = 0.0297 \text{ m} \quad (7)$$

As the above calculation displays, in this scenario of a solid plastic beam, the beam deflects over one inch under load. This deflection would certainly undermine the purpose of the instrument, as the beam when deflected is not supporting the load the ventral wall of the abdomen, but rather deflecting into the operating field to meet the organ. It is understood that a beam with a flexure design (which could only remove material from the solid beam and thus weaken the structure) would deflect more than the solid beam under the same conditions. Thus, with the significant deflection as shown above, it is unlikely that a device fabricated only from plastic could support the required loads without bending. It is important to note that this does not completely preclude the use of plastic, but rather complicates the design; it is entirely possible that plastic reinforced with fiber, metal cable, or bar inserts could sustain the load without significant deformation. While

⁴ “Modulus of Elasticity - Young Modulus for some common Materials” *Engineering Toolbox* n.p. n.d. Web. 10 September, 2013.

an insert molding process would add cost to the manufacturing process and complexity to the design, the process would likely remain less expensive than a solid metal design.

With the understanding that a plastic design without insert molding would likely not sustain the required loads, it was decided that for the purpose of proof-of-concept, the flexure would be prototyped from stainless steel. This steel prototype facilitates the early prototyping process and ensures design for maximum functionality while still keeping design for manufacturing in mind.

3.3.2 Flexure Stops

In order to conform to the shape of the abdomen while still supporting a substantial downward load, the flexure must easily bend to a specified curvature similar to that of the abdomen and support a load once deformed. To accomplish this, metal stops were added in order to prevent bending past the prescribed angle.

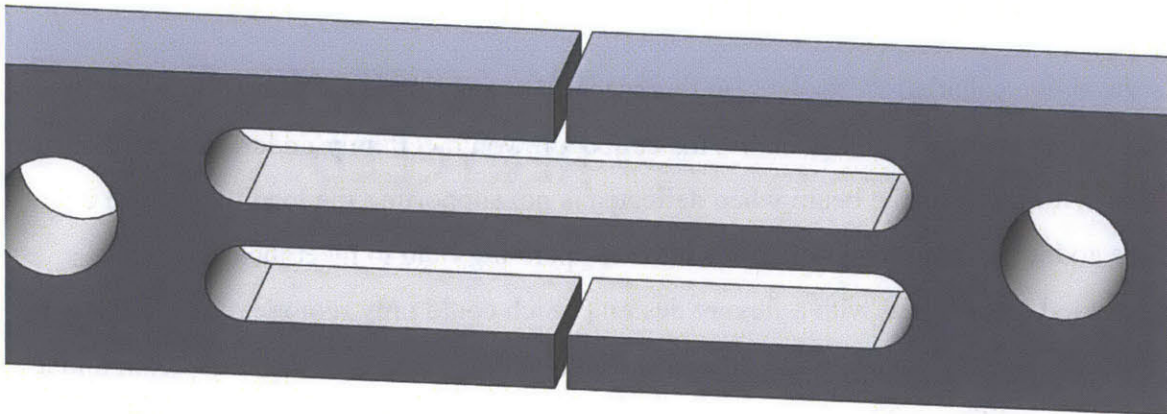


Figure 18: SolidWorks image displaying flexure design including metal stops. When the flexure is deformed, the gap between metal stops closes. Upon contact, the compressive load is transferred from the flexure to the metal stops reducing rate of deformation past the specified angle.

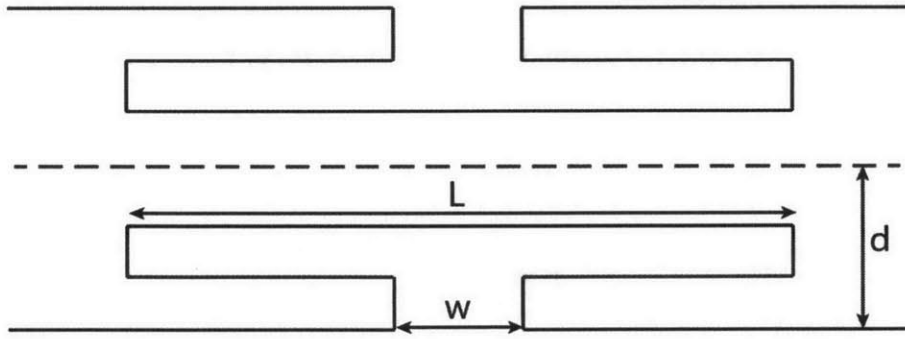


Figure 19: Sketched representation of the flexure. Dotted line represents neutral axis, L represents functional length of the flexing member, w represents the gap between stops.

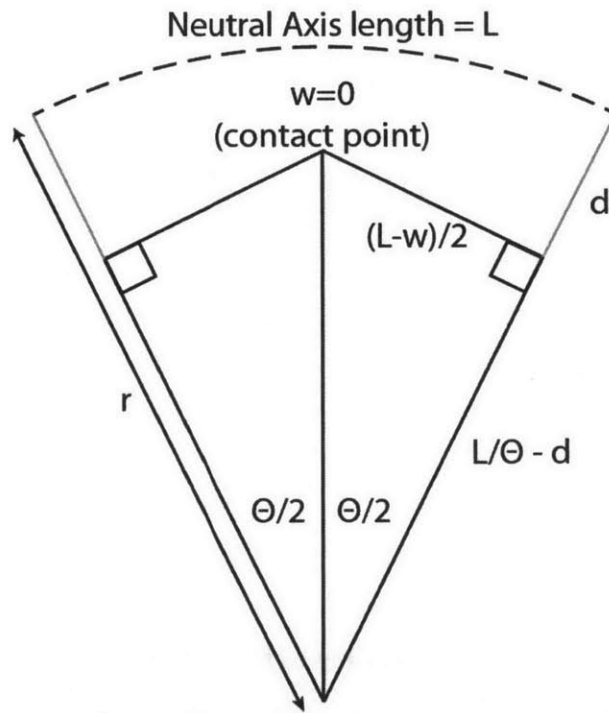


Figure 20: Sketched geometric representation of the flexure when deformed until contact is achieved between stops.

Equations 1-6 display the geometric calculation of the required gap (w) between the flexure stops to achieve a desired angular deformation of θ per flexure link.

$$r\theta = L \quad (8)$$

$$r = \frac{L}{\theta} \quad (9)$$

$$r - d = \frac{L}{\theta} - d \quad (10)$$

$$\tan \frac{\theta}{2} = \frac{\frac{L-w}{2}}{\frac{L}{\theta} - d} \quad (11)$$

$$2 \left(\frac{L}{\theta} - d \right) * \tan \frac{\theta}{2} = L - w \quad (12)$$

$$w = L - 2 \left(\frac{L}{\theta} - d \right) * \tan \frac{\theta}{2} \quad (13)$$

3.3.3 Flexure Bending Stress

To maintain sufficient strength while bending to the required angle with minimal force applied, the thickness of the flexing member must be specifically chosen. Additionally, if the flexure dimensions allow for plastic deformation, the device would fail to re-straighten for removal from the abdomen. This could require the surgeon to convert the laparoscopic procedure into an open procedure causing unnecessary and unacceptable trauma to the patient.

In order to minimize the possibility for plastic deformation, care must be taken to design a flexure that never undergoes plastic deformation. Keeping in mind that stress on the flexure member will result not only from flexing but also from load, a moderate factor of safety must be included in the design.

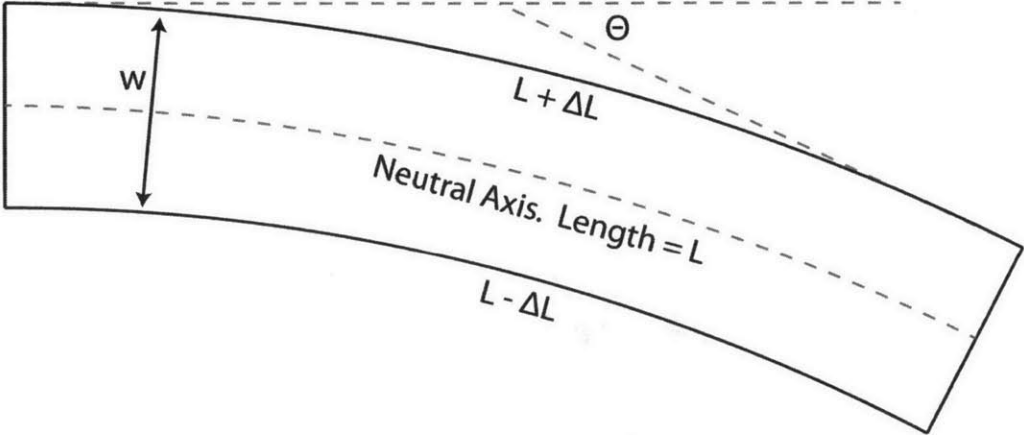


Figure 21: Sketched representation of the flexible member bending under load.

Equations 7-23 show a calculation of maximum possible flexure thickness. Equations 24-26 show calculation of stress for a given flexure thickness chosen below the maximum possible flexure thickness.

$$r = \text{radius at neutral axis} \tag{14}$$

$$L = r\theta \tag{15}$$

$$L - \Delta L = \left(r - \frac{w}{2}\right)\theta \tag{16}$$

$$r\theta - \Delta L = \left(r - \frac{w}{2}\right)\theta \tag{17}$$

$$r\theta - \Delta L = r\theta - \frac{w}{2}\theta \tag{18}$$

$$\Delta L = \frac{w}{2}\theta \quad (19)$$

$$\epsilon = \frac{\Delta L}{L} = \frac{w\theta}{2L} \quad (20)$$

Assumptions

$$l = 0.0127m \text{ (0.5in)} \quad (21)$$

$$\theta = 0.0873 \text{ rad (5}^\circ\text{)} \quad (22)$$

Material Properties

$$\epsilon_{max} = \frac{\sigma_{yield}}{E} \quad (23)$$

17-4 PH SS

$$\sigma_{yield} = 1200 \text{ MPa} \quad (24)$$

$$E = 196 \text{ GPa} \quad (25)$$

$$\epsilon_{max} = \frac{760}{196,000} = 0.0039 = 0.39\% \quad (26)$$

Solve

$$\epsilon = \frac{w\theta}{2L} \quad (27)$$

$$w = \frac{2\epsilon L}{\theta} \quad (28)$$

$$w_{max} = \frac{2 \epsilon_{max} L}{\theta} = \frac{2 * 0.0039 * 0.0127}{0.0873} \quad (29)$$

$$w_{max} = 0.00113 \text{ m} = 0.045 \text{ in} \quad (30)$$

$$\text{Choose } w = 0.00089 \text{ m} = 0.035 \text{ in} \quad (31)$$

$$\epsilon = \frac{w\theta}{2L} = 0.00306 \quad (32)$$

$$\sigma_{bending} = \epsilon * E = 599.6 \text{ MPa} \quad (33)$$

3.3.4 Flexure Load Bearing Stress

Once suspended against the abdominal wall and properly deformed to conform to the abdominal cavity shape, organs will be suspended from the device. These organs will impart a load onto the flexure resulting in stress in addition to the stress caused by beam bending.

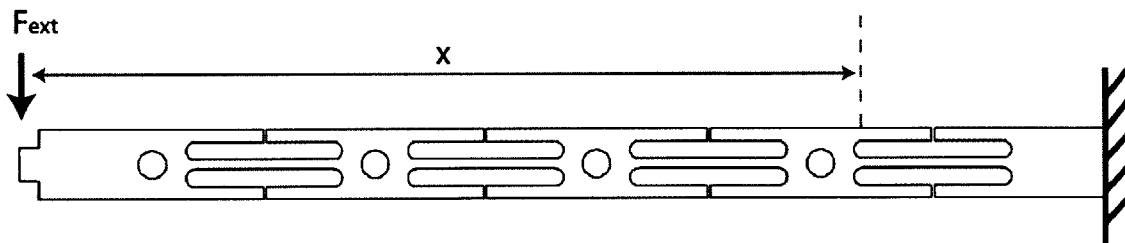


Figure 22: Sketched representation of the device under load while supporting organs. “Grounded” section on the right side represents the center of the device as suspended form the abdominal wall.

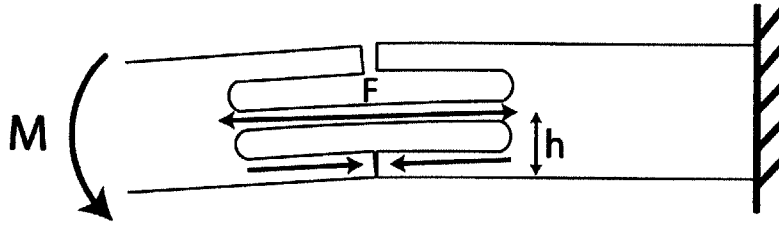


Figure 23: Sketched representation of a single flexure section under load while supporting organs. “Grounded” section on the right side represents the center of the device as suspended from the abdominal wall.

Equations 27-37 show a calculation of the stress induced in the flexure due to a given load at the tip of the beam.

$$\text{Moment Induced by Load} \quad M = F_{ext} * x \quad (34)$$

$$M = F * h \quad (35)$$

$$\sigma_{load} = \frac{F}{area} = \frac{F}{w*t} \quad (36)$$

w = width of flexure

t = thickness of flexure

$$\sigma_{load} = \frac{M}{hwt} = \frac{F_{ext} * x}{hwt} \quad (37)$$

Assumptions:

$$w = 0.00113 \text{ m (0.045 in)} \quad (38)$$

$$t = 0.00381 \text{ m (0.15 in)} \quad (39)$$

$$x = 0.07620 \text{ m (3 in)} \quad (40)$$

$$h = 0.00318 \text{ m (0.125 in)} \quad (41)$$

$$F_{ext} = 15N \quad (42)$$

Calculation:

$$\sigma_{load} = \frac{F_{ext} * x}{hwt} \quad (43)$$

$$\sigma_{load} = 83.5 \text{ MPa} \quad (44)$$

3.3.5 Flexure Total Stress

Summing the calculated stress from beam bending with the stress induced by external loads can approximate the maximum total stress in the flexing member. Keeping the assumptions in sections 3.3.3 and 3.3.4, the total stress induced in the flexible member will be less than the yield stress during normal use. An additional factor of safety of approximately 1.5-2 can be achieved by hardening the 17-4 PH SS after machining. With this factor of safety, we can be confident that the flexure will not undergo plastic deformation during normal use.

$$\sigma_{bending} = \epsilon * E = 599.6 \text{ MPa} \quad (45)$$

$$\sigma_{load} = 83.5 \text{ MPa} \quad (46)$$

$$\sigma_{total} = \sigma_{load} + \sigma_{bending} = 683.1 \text{ MPa} \quad (47)$$

$$FOS = \frac{\sigma_{yield}}{\sigma_{total}} = \frac{1200 \text{ MPa}}{655.3 \text{ MPa}} = 1.76 \quad (48)$$

4. Design Analysis and Future Plans

While both the hinged and flexure designs are capable of meeting the functional requirements of the instrument, the flexure design is preferable due to its manufacturing and assembly simplicity. While it is possible that the hinged version could sustain a higher maximum load as compared to the flexure version, the analysis in section 3.3 shows that the flexure design will be able to sustain the required loads. Given that the flexure design can sustain the required loads and will meet all functional requirements of the device, it is likely that the flexure design will be the most cost practical mass production solution. The flexure design can be fabricated using blanking or molding while the hinged design has dozens of machined parts. Additionally, the flexure design can be fabricated with minimal assembly.

Future work for the project will involve the use of plastic as a flexure material. As calculated in section 3.3.1.1, it is unlikely that plastic without reinforcement could sustain the required load imparted by a suspended organ. This, future investigation will involve the use of fiber reinforced injection molded plastics or plastics reinforced by metal wire or rod inserts. Additionally, future work will involve the use of blanking processes to fabricate the Stainless Steel flexure as designed in section 3.3 with minimum CNC machining time.

Appendix:

Analysis from section 3.2.1

To analyze the feasibility of the Hinged Version 1 design, the stress induced by a lateral load exerting a moment on the joint (Figure 7 and Figure 8), was calculated. This stress was analyzed to ensure that typical use lateral loading does not result in plastic deformation.

$$\text{Beam Thickness } t = .00160 \text{ m (0.063 in)} \quad (49)$$

$$\text{Beam Width } w = 0.00381 \text{ m (0.15 in)} \quad (50)$$

$$\text{Modulus of 17-4PH}^5 \quad E = 196 \text{ GPa} \quad (51)$$

$$\text{Beam Moment of Inertia } I = \frac{wt^3}{12} \quad (52)$$

$$\sigma_x(y) = \frac{M(x)y}{I} = \frac{12 M(x)y}{wt^3} \quad (53)$$

$$\sigma_{max} = \sigma_x\left(\frac{t}{2}\right) = \frac{M(x)t}{2I} = \frac{6 M(x)t}{wt^3} = \frac{6 M(x)}{wt^2} \quad (54)$$

$$\text{Moment from 10 N force at 2 inches} = 20 \text{ inch} * \text{N} \approx 0.5 \text{ Nm} \quad (55)$$

$$\sigma_{max} = 308 \text{ MPa} \quad (56)$$

⁵ “Modulus of Elasticity - Young Modulus for some common Materials” *Engineering Toolbox* n.p. n.d. Web. 10 September, 2013.

References:

1. "FDA permits marketing of a new device for abdominal surgery" *U.S. Food and Drug Administration*. n.p. 1 May 2012. Web. 9 September 2013.
2. "MAGIC Magnetic Retractor" *Pediatric Device Consortium* n.p. n.d. 16 December 2013
3. Elert, Glenn. "Mass of a Human Liver." *Hyper Text Book*. n.p. n.d. Web. 8 September, 2013.
4. "Cross section biomedical illustration of endoscope and tubes inserted in abdomen of adult female during laparoscopic surgery" *Think Stock Photos* n.p. n.d. 16 December 2013 <http://www.thinkstockphotos.com/image/stock-illustration-cross-section-biomedical-illustration/150955033>
5. "Modulus of Elasticity - Young Modulus for some common Materials" *Engineering Toolbox* n.p. n.d. Web. 10 September, 2013.