# Team 11: Autonomous Suture Management Final Report

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## Background

Increasing the level of autonomy in surgical robotic systems could help to standardize patient outcomes and free up surgeons to complete other tasks. This could be particularly impactful for time-consuming and repetitive tasks such as suturing. The Endo360 with Smart Tissue Autonomous Robot (STAR) performs autonomous suturing in laparoscopic surgeries. STAR has been shown to increase the consistency of suturing compared to both traditional manual surgery and non-autonomous robotic surgery [1]. However, STAR's level of autonomy is limited because it requires a human assistant for suture tensioning management in a laparoscopic environment [2].

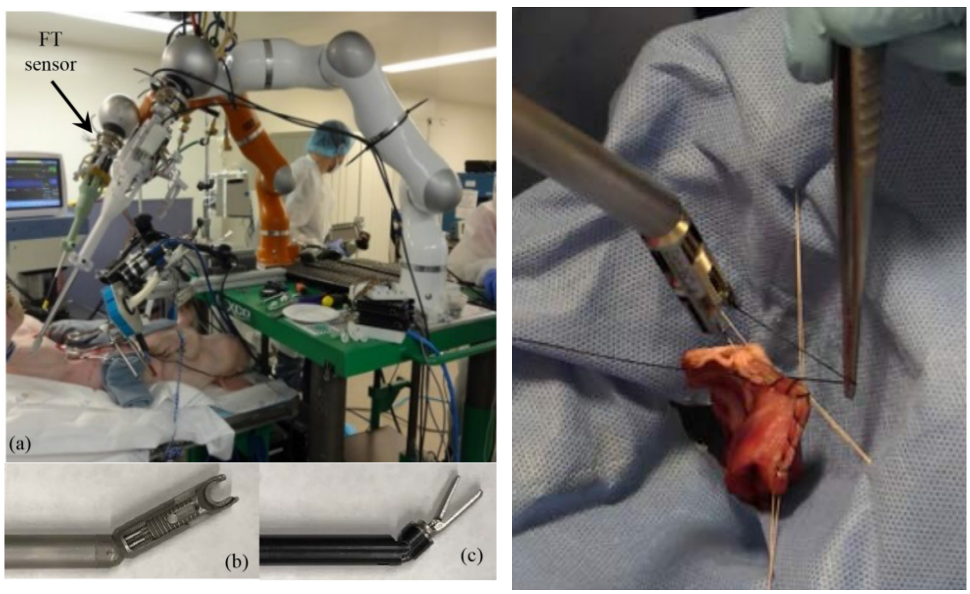


**Figure 1a. (left) STAR autonomous 2-arm open environment setup [1]. 1b (right) STAR robot with manual suture tensioning management [2]**

# Goals

The goal of this project is to develop a device which increases the level of autonomy that the STAR robot can achieve while performing autonomous suturing in a laparoscopic workspace. Our approach to this problem is to create a device which will interface with the autonomous suturing end effector to manage suture tensioning. This device could reduce the workload of the surgeon while helping to standardize patient outcomes.

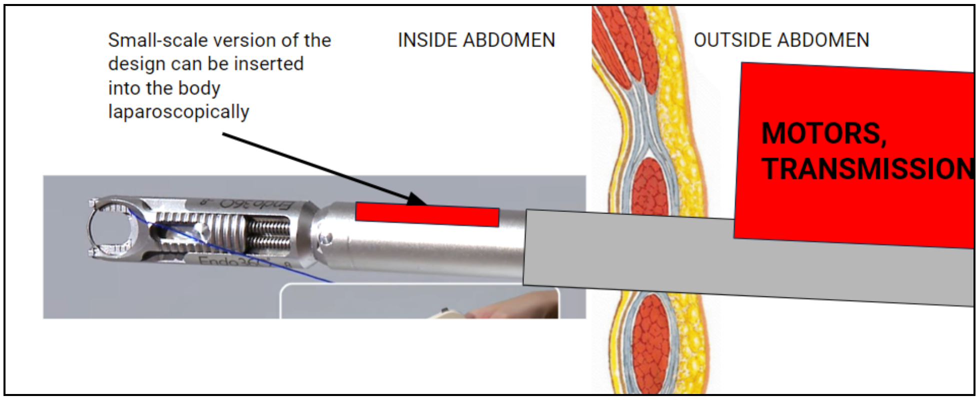


**Figure 2: Diagram of project goal: small-scale mechanism which attaches to the STAR suturing end effector and can be inserted into the abdomen laparoscopically to autonomously manage suture tensioning.**

Working towards this goal, three sets of checkpoints were made:

**Minimum Deliverables:**

1. Large-scale prototype demonstrating mechanism.
2. Test results with large-scale prototype indicating that the prototype is able to catch thread, tension, and release thread on the Endo360 with STAR robot outside of the body.

**Expected Deliverables:**

1. CAD model of small-scale prototype.
2. Large-scale prototype which can be controlled via CANbus.
3. Test results of large-scale prototype against current dual-arm approach of the Endo360 with STAR robot.
4. Test results of CAD model of small-scale prototype indicating that the prototype is able to catch thread, tension, and release thread on the Endo360 with STAR robot.

**Maximum Deliverables:**

1. Small-scale physical prototype that works with the Endo360 with STAR robot and fulfills all requirements specified in the “Design Specifications” document on our wiki.
2. Test results of small-scale prototype against current dual-arm approach of the Endo360 with STAR robot.
3. Conference publication.

# Design

To approach this problem, we first made a design requirements document. This document influenced our design decisions to ensure that we are creating a product which actually solves our problem. Many of our design specifications constrained the size of the device to ensure that it could operate within a laparoscopic workspace. Some of the most notable form specifications are:

1. The prototype must be able to fit into a 25mm diameter tube in at least one configuration [3].
2. Any cross-sectional areas of the prototype with a diameter greater than 25mm must be placed at least 12” back from the tip of the Endo360 on the STAR robot [4].

The next phase of the design process involved brainstorming and prototyping. After brainstorming many different possible solutions with the whole team, we decided to focus on physical prototyping of two designs which we felt were most likely to achieve our design specifications. Note that each of these two designs has a more detailed design document on our wiki.

- Roller prototype design:

  The prototype comprises two parts, one stationary and one swinging, and offers two degrees of freedom as depicted in Figure 3, where the Endo360 points downwards. Motor 1 controls the swinging arm, while motor 2 actuates the fixed rotor responsible for tightening the thread. The device functions by swinging the rotating arm from side to side, pulling the suture through the tissue in the process. The thread is squeezed between the swinging arm and the actuated rotor, while the end of the swinging arm spins passively. The power transmission would occur via a cable system. Note that the fixed and swinging rotors have a complementary shape optimizing the friction to tighten the suture. The team ultimately chose not to move forward with this design because of its large form factor and because it would require two motors, which is more complex than our final design.

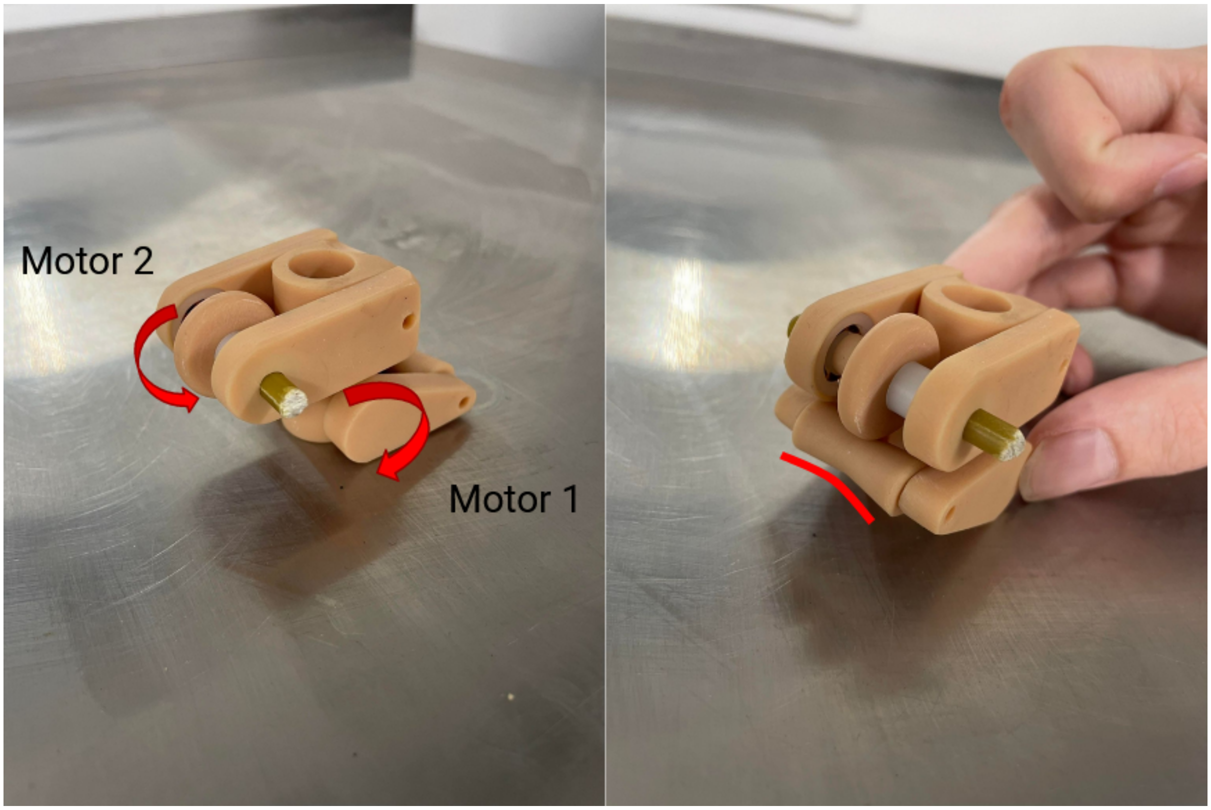


**Figure 3. Roller mechanism of suture tensioning device showing the stationary, the swinging part and the fixed roller which tensions the suture. Note how the fixed and swinging roller have a complementary shape.**

- Gripper prototype design

  The gripper design is displayed in its non-actuated form in Figure 4.a. It works by spinning motor 2 which activates a cable mechanism that opposes the spring force holding the suture tensioning device in its closed configuration, causing it to move to its open configuration (Figure 4b). The thread will be caught between the two rollers on the gripper when the gripper is closed, one actuated and one free-spinning. In the closed position, motor 1 will actuate the driven roller, pushing all the loose thread towards the end effector until a certain current is detected on the motor, indicating that the sutures have adequate tension. At this point, motor 1 will stop moving, and motor 2 will actuate to return the gripper to its open configuration, allowing the STAR to place the next stitch. The team chose not to move forward with this design because of its large form factor, durability concerns with the springs, and because it again required two motors which is more complex than our final design.

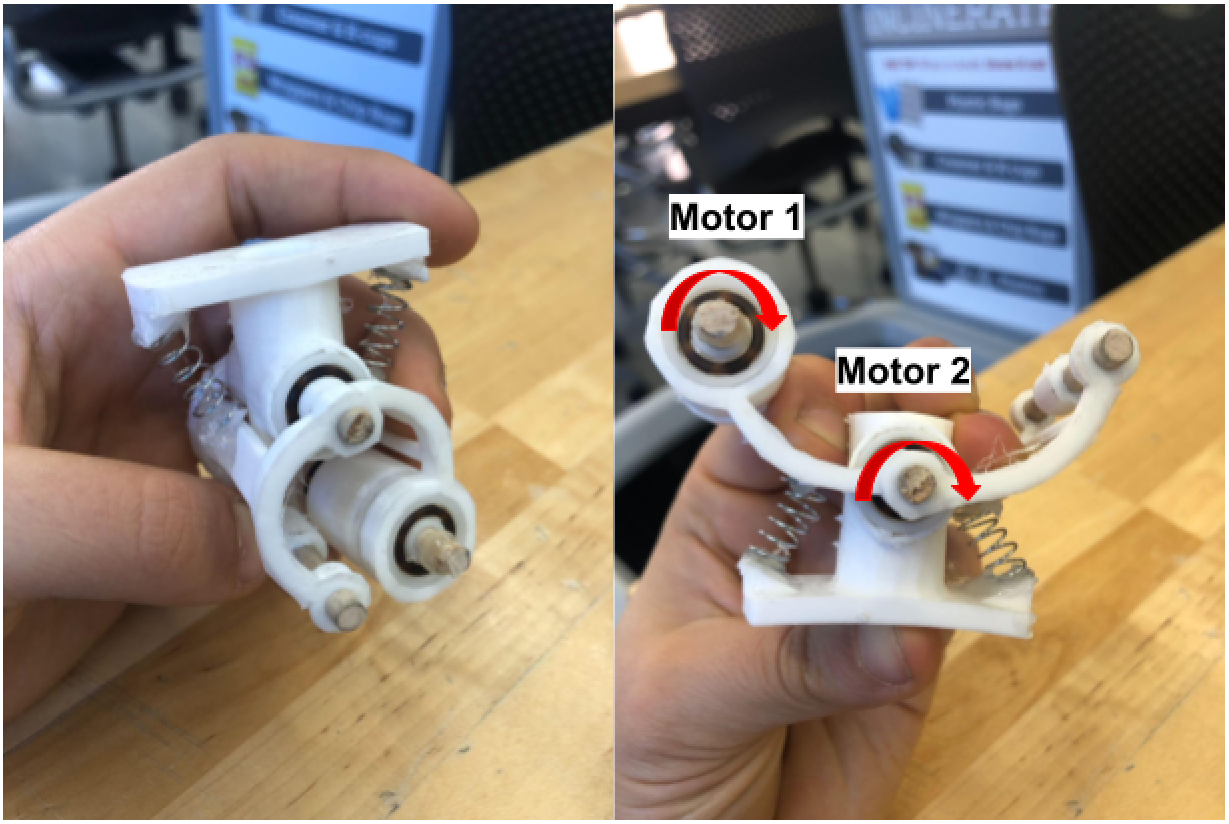


**Figure 4a (left) Gripper design in closed position. 4b (right) gripper design in open position. The springs are responsible for the closing of the mechanism. Motor 1 tensions the thread.**

We decided to move forward with a swinging mechanism design because of its potential for a small form factor and the fact that it only required 1 DOF, and thus only one motor, simplifying our cable transmission system. This design has the most potential to meet our design requirements.

The swinging mechanism (figure 5) catches the thread and tensions it by rotating about a pin joint which causes it to pass by the STAR end effector. The motor actuating the lever arms is placed about 12” up the STAR shaft and transmits power through a cable connection. In the lever arms, the cables are guided by dedicated slots in the arms and fixed using screws. In the transmission part up the shaft, the cables have dedicated slots and guides on the motor spool. They terminate on endpoints by a press fit. The cables wind and unwind on a spool making the entire mechanism swing. Note that both cables are connected to the same motor. Returning to the default position is achieved using torsion springs located in dedicated grooves. These springs make for a straightforward transmission because it allows the mechanism to swing forwards and backwards using only one motor. Both the housing for the levers and the motor housing are fixed to the STAR system shaft using set screws.

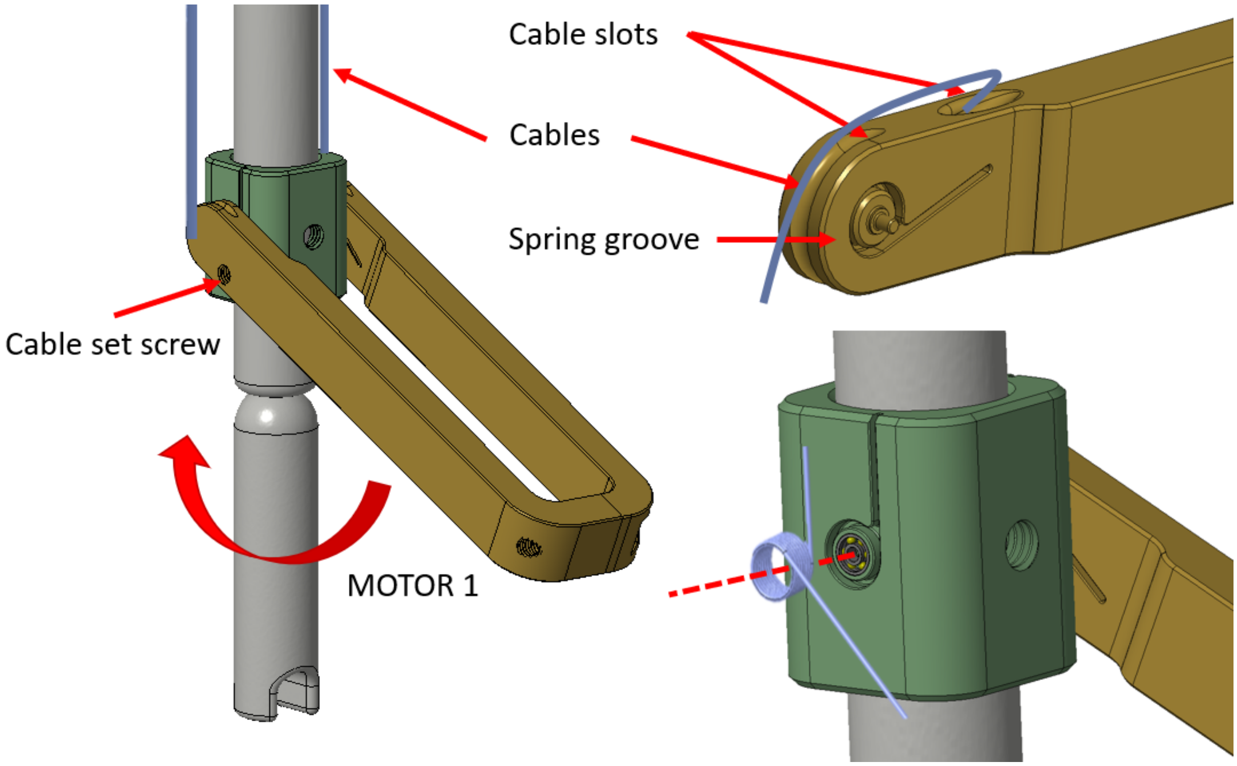


**Figure 5. Swing mechanism of suture tensioning device showing the lever motion, cables, cable set screw, cable slots and spring grooves.**

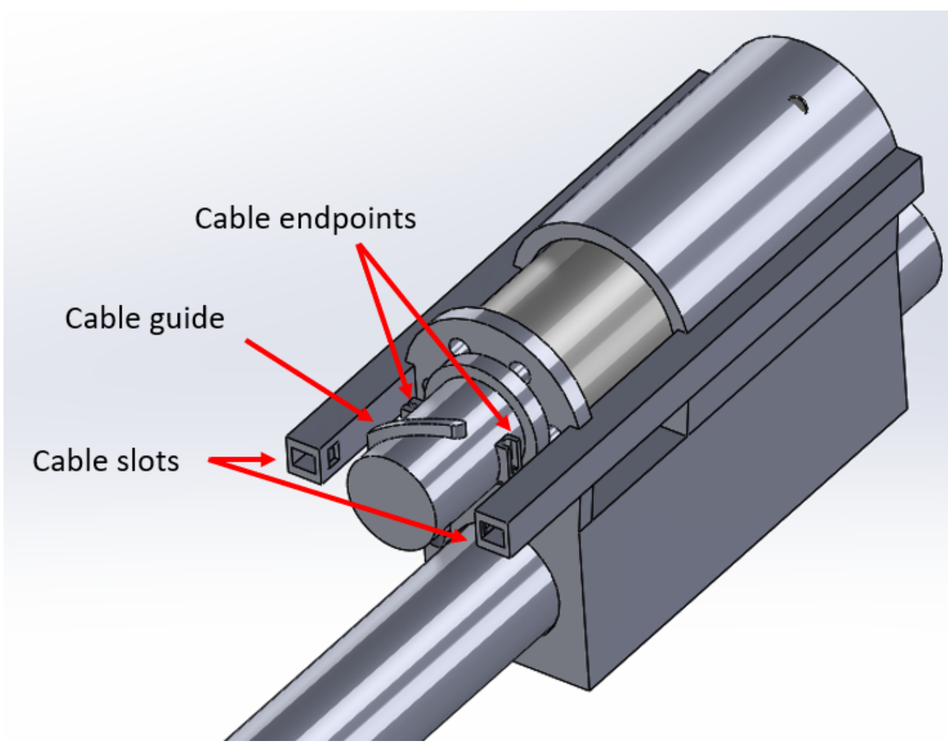


**Figure 6. Transmission pointed on the Endo360 (gripper pointing down). The spool on the shaft of the motor shows the cable slots, guides and endpoints.**

# Testing

Three rounds of testing were performed on the prototype. The first round of testing was a finite element analysis of our CAD model to verify that the prototype could withstand the forces necessary to complete the task. The analysis was carried out using SolidWorks software, taking into account the material properties of Dental Resin, which was used for 3D printing the prototype. The simulation defined the swing mechanism's side surface as a fixture, and gradually increased force applied to the swing mechanism tip. Both structure under normal stress and maximum stress were analyzed. The FFEPlus iterative solver was used to perform this analysis. The mesh density was kept moderate by setting the side length of the mesh triangle to 2.303mm.

The purpose of the second round was to determine the minimum amount of current that we need to send to the motor to result in a force which can apply adequate tensioning to the suture without damaging the tissue. Prior work on autonomous suture tensioning with the STAR robot has found that the ideal force to apply when tensioning sutures to fully tension the thread without damaging tissue is 1N [5].

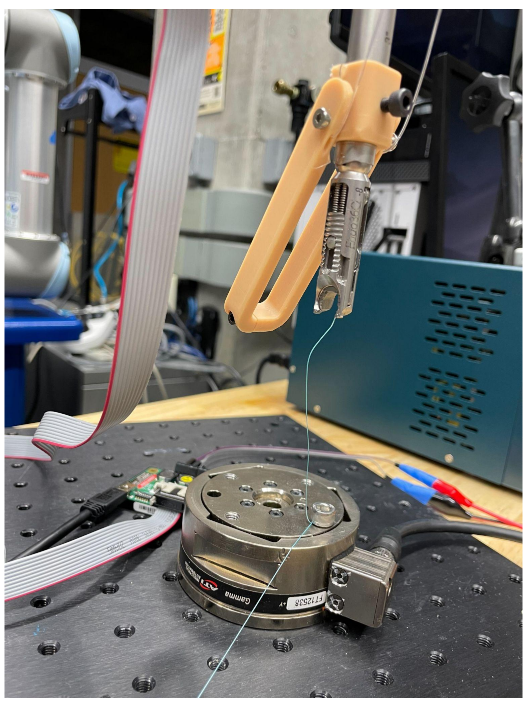

**Figure 7 Force sensor setup below the STAR arm so that the thread is orthogonal to the table.**

To determine the amount of current necessary to send to the motor in our design to result in a 1N tensioning force, we used the setup shown in figure 7. We followed the testing procedure below:

1. Set up the ATI industrial automation multi-axis force sensor on the table directly below the arm of the STAR robot as shown in Figure 7.
2. Tie the suture to a screw on the faceplate of the force sensor.
3. Send a current to the motor via EPOS studio and record the output of the force sensor as the suture is pulled by the swing mechanism. Send currents ranging from 150-350 mA in increments of 50mA to the motor.
4. Plot the relationship of current vs. force. This will allow us to determine the appropriate amount of current to send to the motor to result in a 1N tensioning force which has been shown to be sufficient in [5].

The purpose of the third round of testing was to verify that the prototype was capable of working with the existing STAR system to pull thread through synthetic bowel tissue after the STAR places a stitch without interfering with the STAR system.

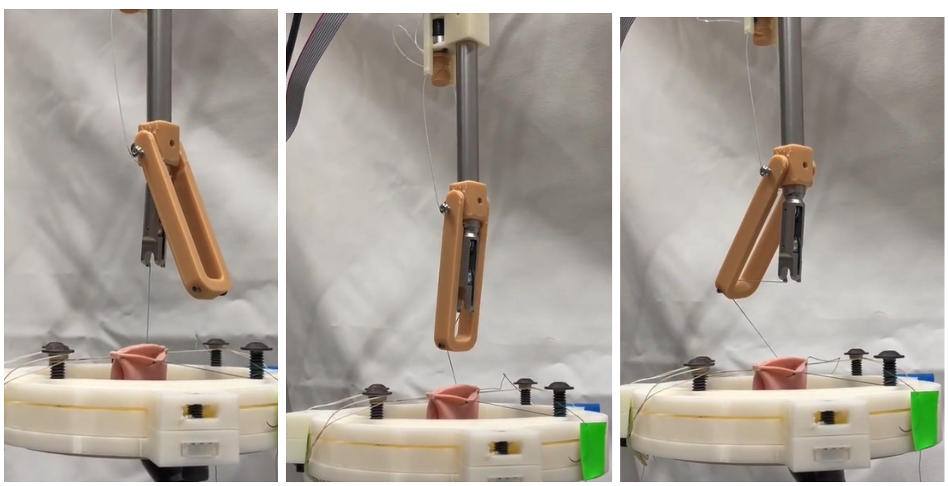

**Figure 8. Synthetic Bowel Testing swing mechanism in starting position (left), contact position (middle), and fully tensioning thread (right)**

To verify that our prototype was capable of working with the functioning STAR system, we followed the testing procedure below:

1. Set up the synthetic bowel tissue (3-Dmed, Franklin, Ohio, USA) into a 3D printed ring setup available to us in the lab as shown in Figure 8.
2. Command STAR to place a stitch.
3. Command our device to swing through to pull tension on the thread and then return to its resting position.
4. Record video and observe whether our device is capable of pulling adequate tension, record whether our device interferes with the STAR system.

# Results & Discussion

**FEA Results:**

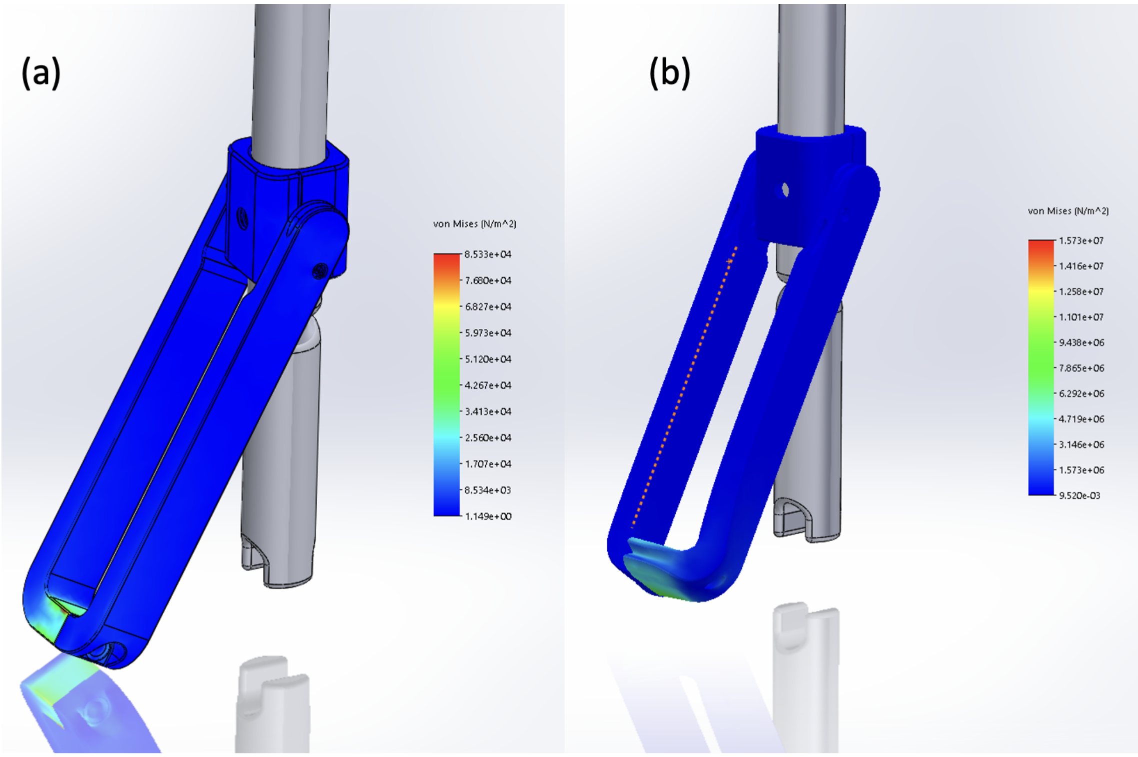


**Figure 9: FEA results of the SMD: a) under normal tension force 0.6N b) under maximum tolerance with deformations.**

The maximum stress was primarily concentrated at the tension rotor's slot. The swing arm's maximum tolerable stress is about 1.315×10^7 N/m2, which means that it can withstand a maximum force of 13.4 N. Since the maximum tensioning force that this device must withstand is known to be about 1N [5], this analysis indicates that the prototype is sufficiently strong for our purposes.

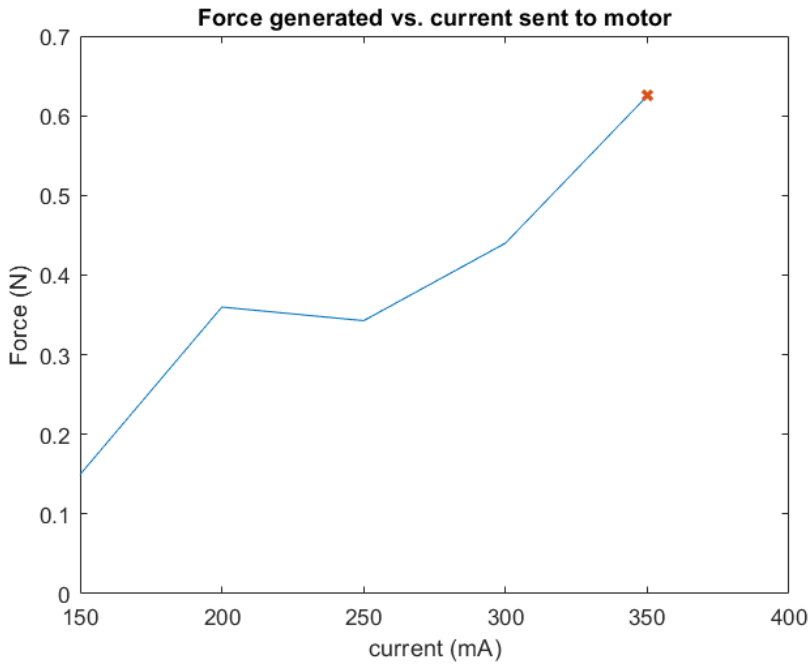


**Figure 10 Force Testing Results. Red x indicates mechanical failure.**

**Force Testing Results:**

The force testing results indicate that our device in its current state is not capable of exerting a force of 1N without breaking. Sending 350mA current to the motor resulted in a 0.6N force on the force sensor. When stepping up to a 400mA current, the torsion springs on the pin joint slipped out of place causing a mechanical failure. Therefore, the maximum force that this prototype is capable of exerting on the suture is 0.6N.

At the time of testing 5/5/2023, the team was still waiting on bearings to arrive (which had been ordered four weeks prior). The team decided to go ahead with assembly and testing without these parts regardless. The team plans to incorporate bearings into the design when they arrive and run this test again at that time. The bearings will significantly strengthen the pin joint, which is where this mechanical failure occurred.

**Synthetic bowel testing results:**

The video of the synthetic bowel testing can be found on our wiki page. We observed that our device was capable of exerting adequate force to pull suture through the synthetic bowel without interfering with the STAR end effector. The speed at which our tensioning system operates is slower than we would like. If we had been able to integrate the bearings into the design, we would have been able to drive the system faster without fear of displacing springs in the swing mechanism. Overall, this design is very promising but several improvements are necessary to allow the STAR system to suture autonomously using our device.

# Team Members & Roles

All team members were involved in mechanical design and prototyping. As a part of our design process, each team member designed and built a physical model of one of our prototype concepts to help us select a concept to move forwards with. Additionally, each team member has individual contributions listed below.

Nathan

- Final swing mechanism design
- Roller prototype design
- Ordering parts

Nyeli

- Physical testing design and documentation
- Gripper prototype design
- Design specifications document

Jiawei

- Motor mount and transmission design
- Finite element analysis testing design and documentation

# Accomplishments and Plan

Most of the deliverables from our minimum, maximum, and expected deliverables were completed later than planned. For our minimum deliverables, the physical large-scale prototype was completed before its expected date, but test results with this prototype were completed 5 days after its expected date.

Our expected deliverables were even more delayed than the minimum because it took more design iterations than we anticipated to arrive at a design capable of fulfilling our requirements. For our expected deliverables, the final CAD model of our small-scale prototype was completed 17 days after expected and the test results with the small-scale design were completed 16 days after expected. The team ended up spending the entire month of April as opposed to the planned first two weeks for iterative prototyping and testing.

However, once we locked our CAD model the process of acquiring and printing parts and assembling the prototype went faster than expected and we were able to complete a physical small-scale working prototype on its expected date. Testing of the physical prototype was completed one day after its expected date. The maximum deliverable of a conference publication was abandoned because it was determined that this was not feasible given the short timeline of one semester.

Overall, the team completed all of its minimum and expected deliverables as well as 2 of the 3 maximum deliverables. Our timeline was different from what we anticipated in that we spent the entire month of April on iterative prototyping, but this process was necessary to arrive at a functional version of the design. In addition to the deliverables, the team also created testing procedure and results documents as well as a design specifications document which were not included in our deliverables. All documents are available as PDFs on our wiki page.

# Next Steps

Immediate next steps with this project include incorporating the bearings into the physical prototype when they arrive and redoing the physical prototype testing with the full design. The system with all CAD models and documentation will remain with the Krieger lab for future improvement and implementation. Jiawei will continue with the Kriger lab working to continue miniaturizing and improving this system and will work towards a conference publication with this system.

# Lessons Learned

We learned that design and prototyping takes longer than we thought and we should have allotted more time to design and prototyping than we did in our initial timeline. We also learned that we should have locked the design a few days earlier or put more effort into finding the specialized very small bearings that we required from a more reliable and faster vendor. Overall, the team members grew in their mechanical design abilities and created a product we are proud of. We are happy with the progress that we have made and the implications of this work for autonomous suturing.

# References


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