Team 11: Autonomous Suture Management Paper Review Report

3/14/2023

Team members: Nyeli Kratz, Jiawei Liu, Nathan Van Damme
Mentors: Michael Kam, Dr. Axel Krieger

CISII Project Goals Review

The goal of our 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. The current highest degree of autonomy (DoA) STAR system has a degree of autonomy of five. This means that the system only requires human decision support, but does not require constant human assistance in suture tensioning management. However, this DoA 5 STAR system is not capable of operating within a laparoscopic workspace [3]. Previous iterations of the STAR system have been capable of operating within a laparoscopic environment, but they required a human assistant to work alongside the STAR system to constantly manage the tensioning of the thread, meaning that its degree of autonomy was only four [2] [3]. The goal of our project is to create a device which allows the STAR system to operate within a laparoscopic workspace at a DoA 5, requiring humans only for decision support rather than for constant suture tensioning management.

To accomplish this goal, we will design a device which will interface with the autonomous suturing end effector. This mechanism will enable STAR to perform single-arm robotic suture management and tensioning. This will reduce the workload of the surgeon and also decrease the invasiveness of STAR procedures, since only one incision site would be needed as opposed to the two which are needed for the current dual-arm approach [3].

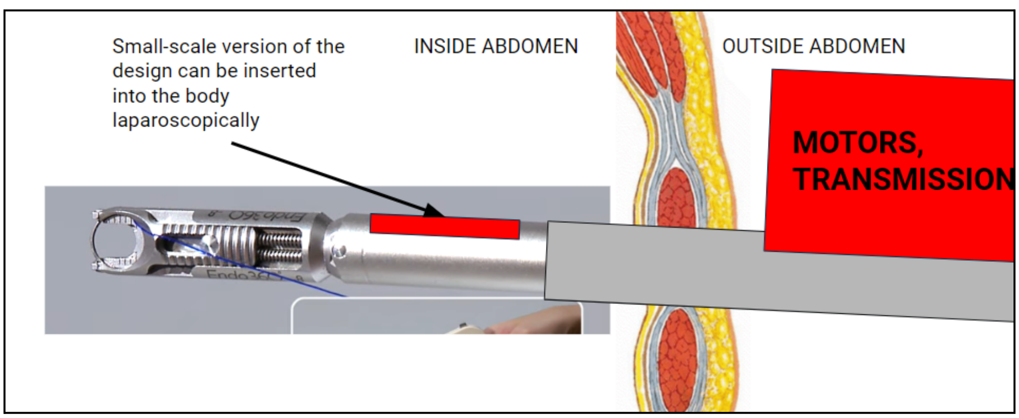

Fig.1: Diagram of project goal: small-scale mechanism which attaches to the STAR suturing end effector and can be inserted into the abdomen laparoscopically to autonomously manage suture tensioning.

Paper 1

Relevance/Selection Motivation

The first paper selected for review is “Autonomous robotic laparoscopic surgery for intestinal anastomosis” by A. Shademan et. al [1]. This paper was chosen because it was the first STAR system to perform an extensive soft tissue surgery task with minimal human interference at a quality which is comparable to that of both human surgeons and teleoperated robot-assisted surgery. This paper provides extensive testing of the STAR system which we can use to evaluate our design as well as data which can be used to compare the performance of our iteration of the STAR system to previous iterations.

Additionally, this paper also provided us with some metrics for tissue deformation that we should expect to occur while tensioning sutures, which will allow us to design for preventing interference between our device and the tissue. This paper also referenced statistical techniques which may be useful in analyzing our test results and provides a relationship between leak pressure and suture spacing variance, verifying an assumption made in our other references [2] [3] that decreased suture spacing variance results in better surgical outcomes.

Intro & Background

Autonomous robot-assisted surgery (RAS) has been shown to improve outcomes in bone surgeries, but as of the publication of this paper, the execution of a complete soft tissue surgery had yet to be performed autonomously. The non-rigid transformations in tissue inherent in soft tissue surgery pose challenges when adapting surgical plans made before the operation. Autonomous soft tissue surgery has the potential to improve safety, efficiency, and consistency of outcomes. Prior to the publication of this paper, attempts at automating soft tissue surgeries had been limited to simple tasks such as knot tying and needle insertion. The goal of this paper was to provide a proof of concept for soft tissue autonomous surgery.

The paper describes the development of a Smart Tissue Autonomous Robot (STAR), which is a supervised autonomous robot designed for performing complex surgical tasks. The robot is equipped with smart imaging technologies, including plenoptic 3D surface reconstruction and a near-infrared fluorescent (NIRF) imaging camera. The system was tested by performing an ex vivo end-to-end anastomosis and an in vivo end-to-end anastomosis of porcine small intestine. Finally, performance metrics are compared between STAR and manual open surgery (OPEN), manual laparoscopy (LAP) and laparoscopic RAS (RAS).

Methods

Robotic platform: The STAR system consists of a KUKA LWR arm. Fixed to the end-effector is a 1 DOF Endo360 automatic suturing device making the total system 8 DOF. Custom control software had to be developed to deal with the forward and inverse kinematics. A force sensor was placed between the last link and the Endo360 to measure suture tensioning.

Imaging system: A special NIR fluid was created for tissue tracking. The liquid is administered to the target using a syringe. This allows for a point cloud to be detected by a NIR camera. 3D reconstruction of the tissue was possible using a separate plenoptic camera.

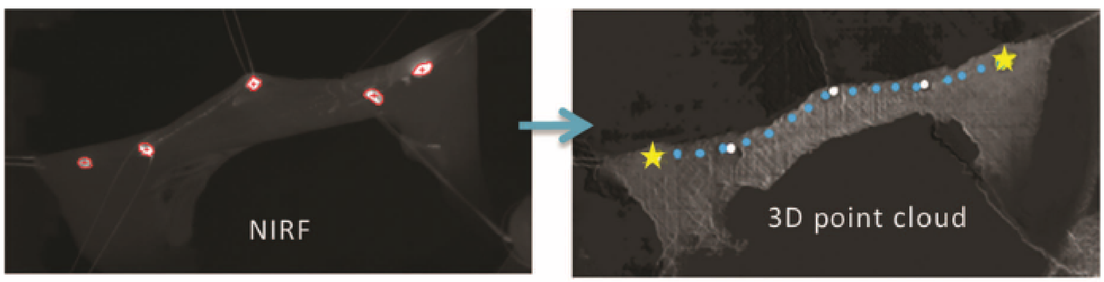

Fig.2: NIRF picture showing administered markers (left), 3D plenoptic camera image showing point cloud registration (right) [1]

Control strategy: The software requires information about tissue depth and cut length either by sensors or user input. The software is then able to generate a suturing plan with evenly spaced sutures using the combined NIRF and 3D plenoptic vision system. This plan is updated in real time and adjustments could be made by the surgeon in supervision mode.

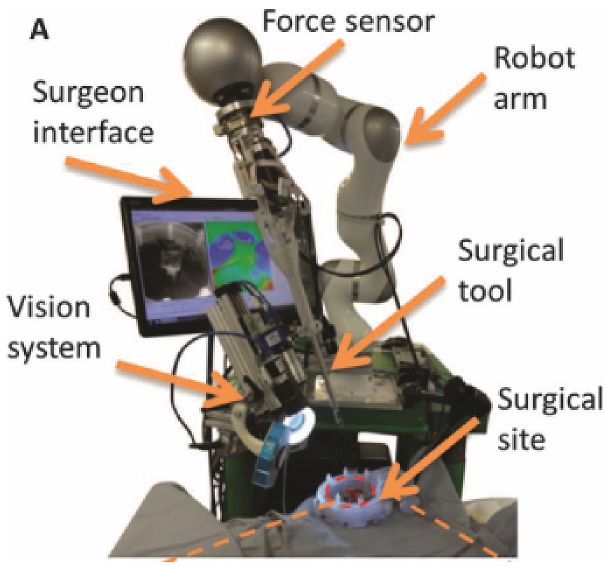

Fig.3: full STAR system with integratedNIRF and 3D plenoptic vision system, force sensor, KUKA arm and Endo360 tool [1]

Experiment: The system was evaluated by performing an ex vivo end-to-end anastomosis and an in vivo end-to-end anastomosis of porcine small intestine. Performance metrics are compared between STAR and manual open surgery (OPEN), manual laparoscopy (LAP) and laparoscopic RAS (RAS) with a sample size of 5 for each group. Suture spacing, leak pressure, number of mistakes, and completion time were compared across groups.

Results

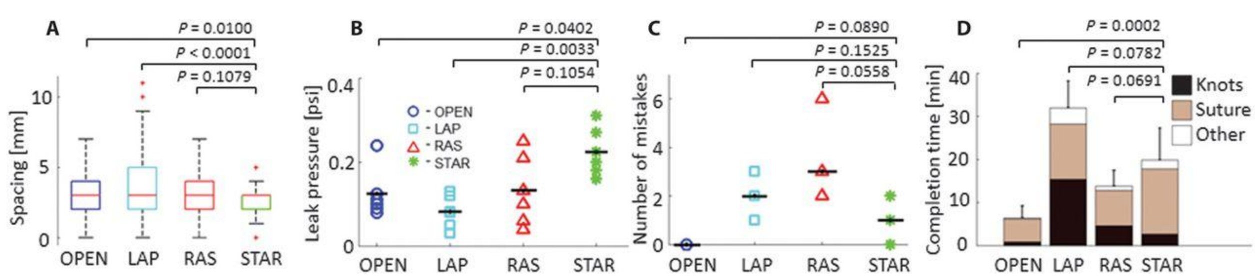

Fig.4: Spacing results across groups (4a), Leak pressure results across groups (4b), number of mistakes (4c) and completion time (4d) [1]

Ex vivo end-to-end anastomosis: STAR performed significantly better than the current standards of care for OPEN, LAP, and RAS techniques in suture spacing variance for ex-vivo end-to-end anastomosis (Fig.4a). The average suture spacing by STAR was significantly less than LAP and RAS, but was similar to OPEN (Fig.4a). There was an inverse relationship between maximum suture spacing and leak pressure, with a root mean square error of 0.11 psi. This led the researchers to conclude that the more consistent suture spacing of STAR contributed STAR's ability to withstand higher leak pressures, nearly double the pressure compared to all other manual techniques (Fig.4b).

The STAR system also had fewer mistakes than LAP and RAS, less than one mistake per sample that required repositioning of the needle (Fig.4c). The average completion time by STAR was significantly longer than OPEN and RAS, but comparable to LAP (Fig.4d).

Table.I In vivo end-to-end anastomosis results compared between STAR and OPEN [1]

Metric	STAR 1	STAR 2	STAR 3	STAR 4	OPEN control
Procedure time (min)	57	67	41	35	8
Number of sutures	20	23	16	17	25
Number of suturing mistakes	0	2	1	1	0
Leak pressure (psi)	0.22	>1.2*	>1.2*	N/A†	0.23
Luminal diameter reduction (%)	33.3	25.9	13.3	7.1	6.3
Weight at surgery (kg)	18	20	16.4	22.1	21.4
Weight at sacrifice (kg)	20	22	18.1	23.8	22.4

In vivo end-to-end anastomosis: The researchers also performed in vivo supervised autonomous surgery using STAR (*n* = 4) and compared these results with an OPEN control (*n* = 1). The average (±SD) STAR procedure time was 50.0 ± 14.7 min, which was significantly longer than the OPEN time (8 minutes). Other metrics including leak pressure and number of mistakes were not significantly different between STAR and OPEN.

Critical Review

Pros:

1. This paper performed exhaustive testing and statistical analysis, particularly for their ex-vivo results.
2. Data from seven different surgeons was used for ex-vivo testing the performance of manual open and laparoscopic surgery. This is a significantly larger data set than other works [2] [3].

Cons:

1. STAR surgery was performed in an open environment (not laparoscopic) but its completion time was significantly longer than human open surgery and was only comparable to that of human laparoscopic surgery. This indicates that as of this publication there is a lot of work left to be done on increasing the speed of the STAR system.
2. The need to place NIRF markers interferes with the surgeon's workflow. This is later addressed in S. Leonard et. al [3] where the suture is coated in NIRF material to eliminate the need for marker placement.

Key Lessons

The most important result from this paper for our work is that the consistency and accuracy of STAR suture placement significantly outperforms teleoperated robot-assisted surgery, humans in open surgery, and humans in laparoscopic surgery. This paper provided initial validation for the concept of autonomous soft-tissue surgery. This provides validation for our project as a whole, suggesting that autonomous soft-tissue surgery, particularly using the STAR system, could potentially both reduce the workload of human surgeons and improve patient outcomes.

Additionally, this paper described testing of the system in detail and provided testing and data which we can use to directly assess the efficacy of our system in comparison with previous iterations of STAR. Some of the metrics which we will use to evaluate our device include time per stitch, number of mistakes, distance between stitches and the variance in distance between stitches, and bite size. This paper established a relationship between suture spacing variance and leak pressure which we can use as validation that a lower suture spacing variance is associated with better surgical outcomes.

Paper 2

Relevance/Selection Motivation

The second paper selected for review is "Autonomous Laparoscopic Robotic Suturing with a Novel Actuated Suturing Tool and 3D Endoscope," by H. Saeidi et. al [2]. This paper was chosen because it evaluates the current highest degree of autonomy (DoA 4) STAR system which is capable of operating within a laparoscopic workspace. This paper was also selected because it describes the design of the novel multi-axis autonomous suturing tool end effector which is used in the current STAR system and which our device will be directly interfacing with.

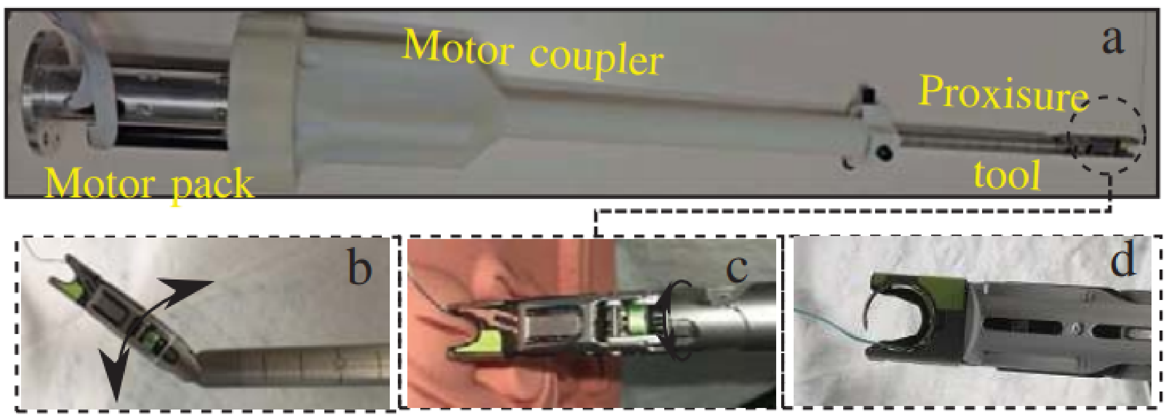

Fig.5: STAR's novel 6-DOF End Effector [2]

Additionally, this paper shows the STAR autonomous suturing workflow, outlining the tasks which our tensioning device must perform. This affects our design requirements and allows us to ensure that our device can interact with the suturing end effector without interfering with it.

Intro & Background

Teleoperated robot-assisted surgery (RAS) systems, like the da Vinci robot, have been shown to improve surgical outcomes in many instances. However, autonomous surgical robots have the potential to further improve consistency in procedures while also reducing the workload of human surgeons.

In this paper, the STAR robot was evaluated for suturing within a laparoscopic environment as opposed to the open environment which was used in A. Shademan et. al [1]. STAR's tissue tracking system was improved to detect breathing, apply noise filtering, detect collisions and reconstruct the tissue in 3D. Additionally, a novel 6-DOF end effector, which is still used on the current iteration of the STAR system, was designed and implemented into the system.

Methods

Imaging system: The imaging system consists of an NIR camera and a monochrome camera. The monochrome camera is used to reconstruct a 3D point cloud of the tissue while the NIR camera is used to track NIR markers placed on the tissue. Together, they allow a full 3D reconstruction of the tissue.

Robotic platform: 2 KUKA LBR were used in the setup. 1 arm holds the motorized Endo360 which allows the sutures to be placed automatically (the classical STAR system). The other arm holds the imaging system. The suturing arm is retracted every time point cloud registration is performed.

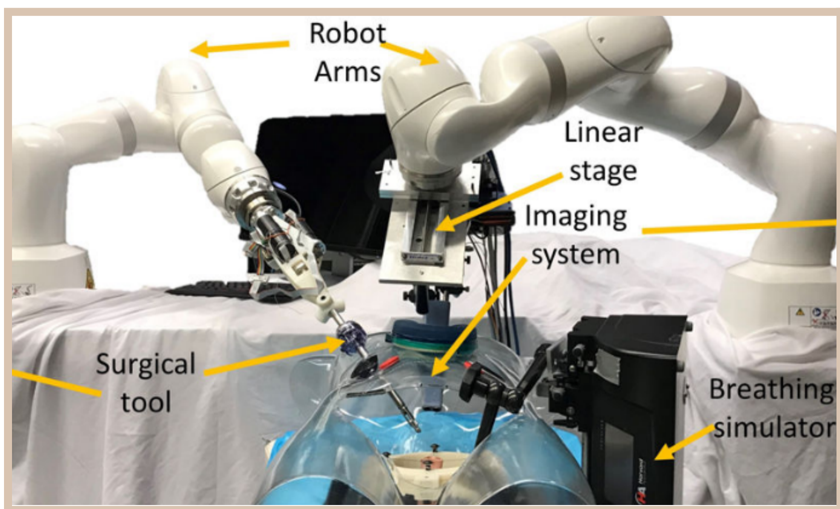

Fig.6: STAR system setup [2]

Control strategy: real-time video frames are collected from the imaging system and processed. These are used in conjunction with the NIR markers for the tissue motion tracking. The system waits until a stationary situation is detected to collect data for further planning. They opted for these 'not breathing' images since they have reduced motion blur. Following this, multiple surgical plans are generated. In doing so, the system predicts the tool position during the procedure and looks at possible collisions between tools and tissue. A new plan can be generated if the operator wishes so. If the operator agrees, the plan gets executed. When the robot places a stitch, the assistant has to manually manage suture tensioning before the robot can continue.

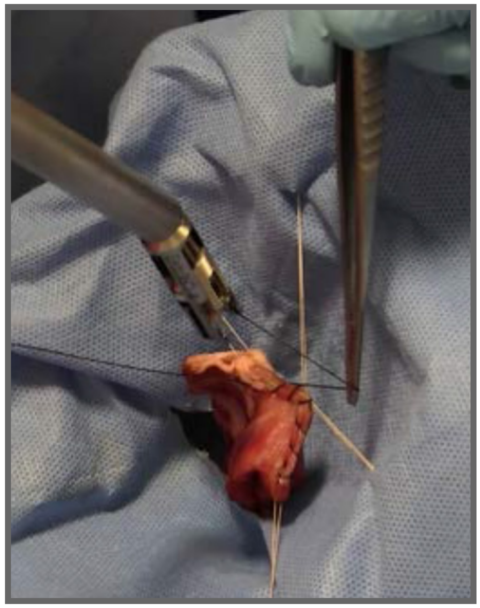

Fig.7: Manual suture tensioning management [3]

Experiment: One knot and three running stitches were used to close an incision in synthetic skin in a laparoscopic environment. With a sample size of 5, the results of two different expert surgeons performing the task manually were compared to the results of the STAR completing the same task. Metrics including bite size, completion time, and suture spacing were compared.

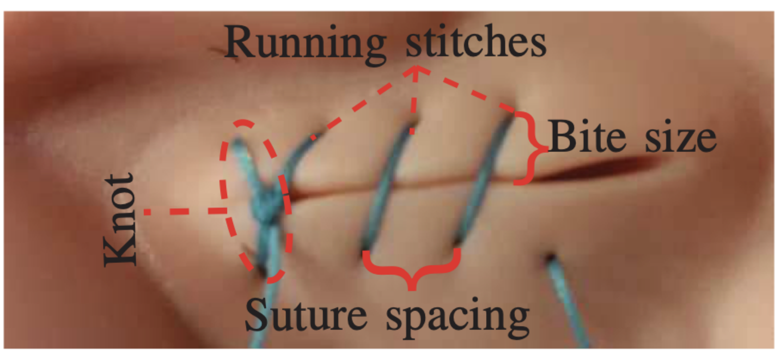

Fig.8: Experimental metrics [2]

Results

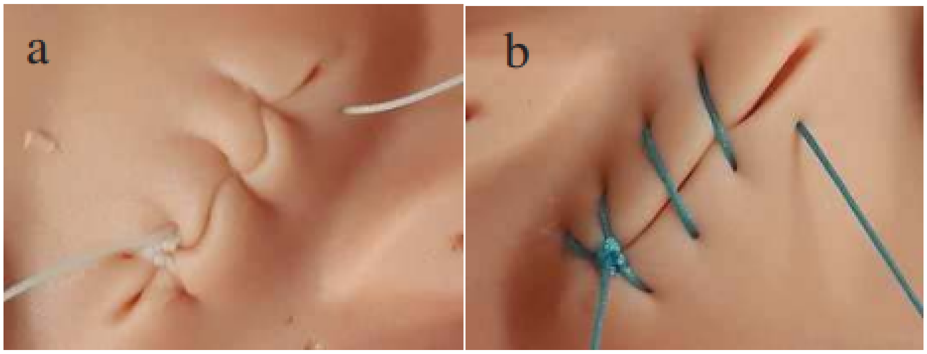

Fig.9: Manual laparoscopic (left) vs. STAR laparoscopic incision closure (right) [2]

The average total task completion time for the autonomous method is 106.4 seconds longer than the manual method (Table II.a), which indicates a need to reduce this time in future iterations of the STAR system. The desired value of suture spacing for STAR is 4 mm and the experimental average is 4.7 mm, indicating significant error in suture spacing (Table II.b). The variance in suture spacing is significantly less for STAR than manual surgery $p < 0.001$ which indicates that STAR placed the running stitches 2.9 times more uniformly compared to the human surgeons. Human surgeons made an average of 1.6 suture corrections per each test while STAR made zero corrections per test. STAR outperformed human surgeons in suture spacing consistency and and number of mistakes, but it underperformed in regards to speed and suture spacing accuracy.

	Total (sec)		Knot (sec)		Stitches (sec)	
Test	Avg.	Std.	Avg.	Std.	Avg.	Std.
Manual	180.20	13.53	92.2	17.28	88.00	9.59
STAR	286.60	6.68	175.4	6.34	111.2	5.56

	Dist between stitches (mm)		Bite size (mm)		Number of repositioning	
Test	Avg.	Std.	Avg.	Std.	Avg.	Std.
Manual	3.68	1.19	2.53	0.86	1.60	0.80
STAR	4.70	0.41	3.41	0.83	0.00	0.00

Table II.a (Top) Comparison of manual vs. STAR results for completion time in seconds. Table II.b (bottom) comparison of manual vs. STAR results for mistakes, bite size, and suture spacing [2]

Critical Review

Pros

1. This paper explains the novel 6-DOF end effector hardware in detail. This will allow us to design our device to prevent interfering with the function of the existing end effector.

Cons

1. The STAR and human surgeons only performed three stitches which is not enough to adequately evaluate the variance in suture spacing.
2. Manual surgery was only performed by two different surgeons. This small sample size makes the results less meaningful.
3. The STAR system was only evaluated against manual laparoscopic surgery, not against teleoperated RAS. There is no way of saying from these results whether an autonomous robot is really necessary to decrease variance in suture spacing or whether this could have been accomplished by a teleoperated robot.

Key Lessons

The most important result from this paper for our work is that the STAR completion time is over 30 seconds per stitch longer than manual laparoscopic surgery. When it comes to complex laparoscopic procedures, this added time under anesthesia would have a negative impact on the patient as well as hospital resources. Therefore, one of the primary goals of our project is to reduce the time per stitch of the STAR system. We plan to accomplish this using mechanical safeguards to prevent our device from interfering with the STAR end effector so that the system will not need to rely so heavily on computer vision and complex control algorithms for all movement.

Another key lesson from this paper is the configuration space of STAR's novel 6-DOF suturing end effector. Because our device will be directly mounted to this end effector, it is critical for our team to understand how it works to avoid constraining the motion of the end effector with our device or interfering with STAR's suturing workflow, which has already shown to be effective in many works [1] [2] [3].

Paper 3

Relevance/Selection Motivation

The third paper selected for review is “Vaginal Cuff Closure With Dual-Arm Robot and Near-Infrared Fluorescent Sutures,” by S. Leonard et al [3]. This paper was chosen because it evaluates the current highest degree of autonomy STAR system (DoA5) and reveals many of the flaws in the current system which we will attempt to address in our device. This STAR system is able to suture fully autonomously with a second autonomous robot arm controlling the tensioning. However, this iteration of the STAR still requires two arms which means that this system requires an extra incision and also has a workspace which is currently too large to operate within a laparoscopic environment. The primary aim of our project is to decrease the workspace of this system while maintaining its level of autonomy, only requiring human decision support as opposed to constant manual assistance.

Intro & Background

Prior to this publication, it had been shown that STAR has increased quality and consistency over manual and even traditional dual-arm robotic approaches. However, at the time of this publication, STAR was still reliant on a human assistant to manage suture tensioning. Without proper suture tensioning management, loose thread can accumulate and interfere with the suture path resulting in a locking thread. Additionally, previous iterations of the STAR system have required NIR markers to be placed on the tissue manually which interrupts surgical workflow.

The paper attempts to solve the aforementioned issues by introducing a robotic assistant arm which is responsible for suture tensioning management. On top of that, the suture itself is coated with NIR markers, meaning that the surgeon no longer needs to manually place markers on the tissue. The results of these new implementations in the STAR system are evaluated on an ex-vivo porcine vaginal cuff closure procedure, an important step in a hysterectomy procedure in which a woman’s uterus is removed.

Methods

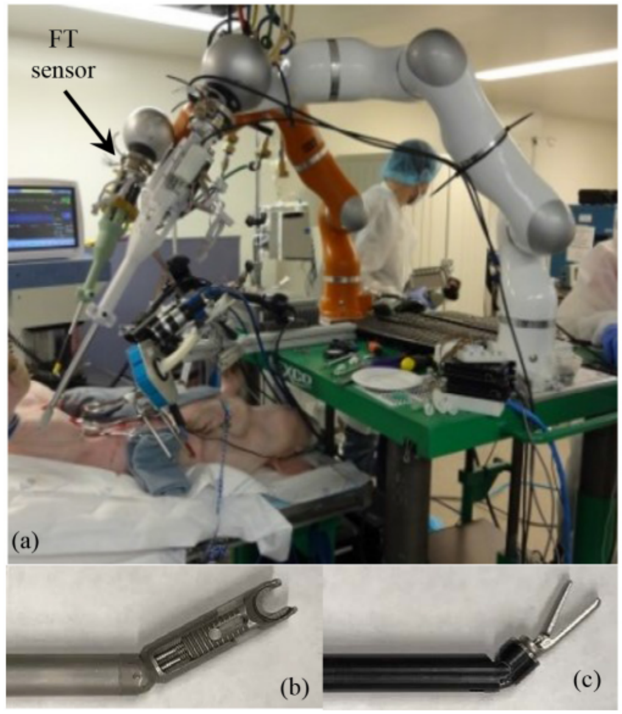

Fig.10 Full STAR system setup with robotic assistant arm (10a). Suturing end effector (10b). Tensioning management end effector (10c) [3]

Robotic platform: 1 KUKA arm was equipped with the motorized Endo360 and a force sensor (Fig. 10a). The other KUKA arm was equipped with a laparoscopic grasper intended to tension the suture (Fig. 10c).

Imaging system: The same STAR vision system from [2] was used: a plenoptic camera for 3D point registration and a NIR camera for NIR tracking. The imaging system uses dedicated algorithms for suture detection and suturing boundaries. We will not go into detail since they are less relevant for this specific project.

Control strategy:

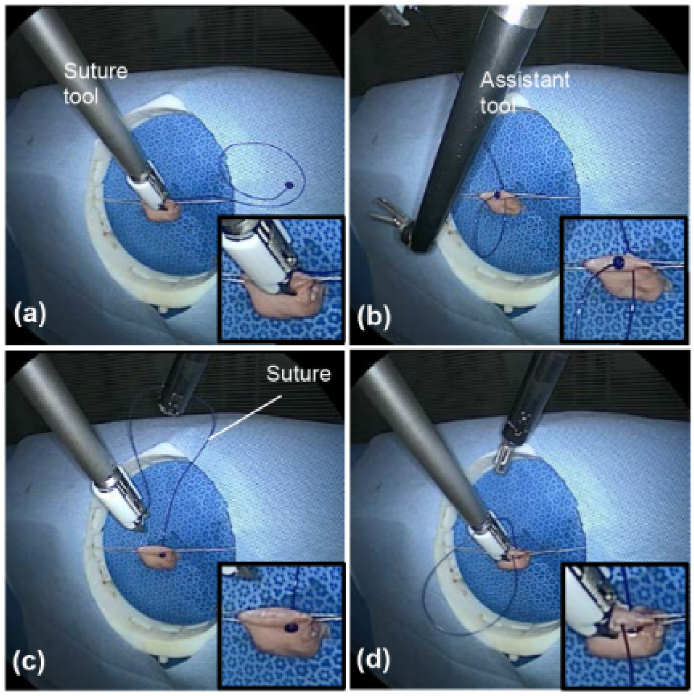

Fig.11: tool positioning workflow during vaginal cuff closure [3]

- **Apply stitch:** Displayed in Fig.11a, the suturing tool moves to its target and applies a stitch. After that the suturing tool moves to create space for the assistant tool.
- **Prepare tension:** The vision system detects the 2 endpoints of the suture in 3D. The assistant tool moves beneath the midpoint and bends its wrist. This gives the tool a ‘V’ shape ready to grip the loose hanging suture thread.
- **Tension stitch:** The assistant tool catches the thread by moving up, catching the midpoint. It continues by moving to the side across the entire workspace, tensioning the suture in the process. The tensioning is stopped when the force sensor detects a force of 5N. Note that during the tensioning, the suturing tool can start a new stitch.
- **Release:** Shown in Fig.11d, the assistant tool unbends the wrist releasing the suture tension and letting the thread fall.

Experiment: Ex-vivo porcine vaginal cuff closure was performed. With a sample size of 6 for each group, the performance of STAR with a robotic assistant was compared to the performance of STAR with a human assistant, Teleoperated robot-assisted laparoscopic surgery, and manual laparoscopic surgery. Metrics including bite depth, completion time, and suture spacing were compared.

Results

Table.III Ex-Vivo Vaginal Cuff Closure Experimental Results [3]

Modality	Time per knot (seconds)	Time per stitch (seconds)	# of mistakes	Suture spacing (mm)	Bite depth (mm)
STAR (with robotic assistant)	54.00 ± 2.61	23.38 ± 2.52	1	2.63 ± 1.66	3.29 ± 1.32
STAR (with human assistant)	83.74±43.60	45.63±9.46	5	2.60±1.04	n/a
LAP	215.67±49.42	92.15 ± 41.93	30	4.22 ± 2.64	3.80 ± 1.70
RAS	202.17±27.93	103.38±44.57	13	5.05 ± 2.42	2.30 ± 1.49

The STAR with a robot assistant made only one mistake across all six tests while the LAP and RAS procedures had 30 and 13 mistakes respectively. Although this result was not statistically significant ($p > 0.05$), this does indicate STAR's potential for improving the consistency of surgical procedures. Additionally, STAR's suture spacing was significantly more consistent than LAP and RAS ($p < 0.05$). The average bite depth variance was not significantly different across the four groups.

Overall, the performance of the STAR with the robotic assistant was very similar to the performance of the STAR with the human assistant. The number of mistakes, suture spacing, and suture spacing variance were nearly identical between the two STAR groups and time per knot and stitch were improved for the robotic assistant system. This demonstrates the potential of an autonomous robotic suture management assistant to reduce suturing time of the STAR system while maintaining its consistency.

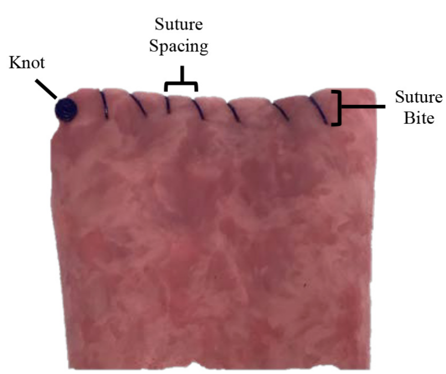

Fig.12: Suture spacing and bite metrics for ex-vivo porcine vaginal cuff closure [3]

Critical Review

Pros

1. This iteration of the STAR system is the first to attempt autonomous suture management and has done so successfully in open surgery. The system has reached a degree of autonomy of 5, meaning that it only relies on humans for decision support.
2. This paper explains the force-torque sensor-based tensioning decision well and provides data which we can use in our design requirements to ensure that our system is applying appropriate forces without damaging tissue.

Cons

1. This STAR system was only tested in open surgery. The workspace is too large for a laparoscopic environment and just because the computer vision system worked well in an open environment with a fixed camera does not mean it will work well in a laparoscopic environment with a moving camera.
2. The relatively small sample size of N=6 for each of the three classes (STAR, LAP, and RAS) is not enough for convincing statistics.

Key Lessons

The most important takeaways for our project are the flaws with the current highest DoA STAR system. Most importantly, the workspace of this current autonomous two-arm approach is much too big to fit into a 10 cm^3 laparoscopic workspace and requires a potentially unnecessary extra incision by the nature of its two-arm design. These flaws have directly contributed to the design requirements of our project. Our device must be capable of tensioning 25 cm of thread within a 10 cm^3 workspace and also collapse into a circle of diameter 15 cm or less around the STAR end effector so that the robot can be inserted into and operate within a laparoscopic environment. We believe that creating a tensioning device which mounts to the suturing end effector will mean that STAR only requires one arm to perform autonomous suturing, eliminating many of the workspace and time constraint issues of previous iterations of the STAR system.

Additionally, this paper provided significant verification for a force/torque sensor-based tensioning management system. This system senses the current that the tensioning motor is drawing and uses this to compute the torque on the motor as an estimate of how much tension is in the thread. Using this system, the research team was able to successfully “tell” the arm when to release the suture before pulling hard enough to cause tissue damage. Thus, our team plans to use the same approach to detect when the thread has been adequately tensioned for each stitch.

References

[1] A. Shademan et al., “Supervised autonomous robotic soft tissue surgery,” Science Translational Medicine, vol. 8, no. 337, pp. 337-345, 2016, doi: https://doi.org/10.1126/scitranslmed.aad9398

[2] H. Saeidi et al., "Autonomous Laparoscopic Robotic Suturing with a Novel Actuated Suturing Tool and 3D Endoscope," 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 1541-1547, doi: https://doi.org/10.1109/ICRA.2019.8794306

[3]S. Leonard et al., "Vaginal Cuff Closure With Dual-Arm Robot and Near-Infrared Fluorescent Sutures," in IEEE Transactions on Medical Robotics and Bionics, vol. 3, no. 3, pp. 762-772, Aug. 2021, doi: https://doi.org/10.1109/TMRB.2021.3097415