Autonomous Suture Tensioning Management Paper Review

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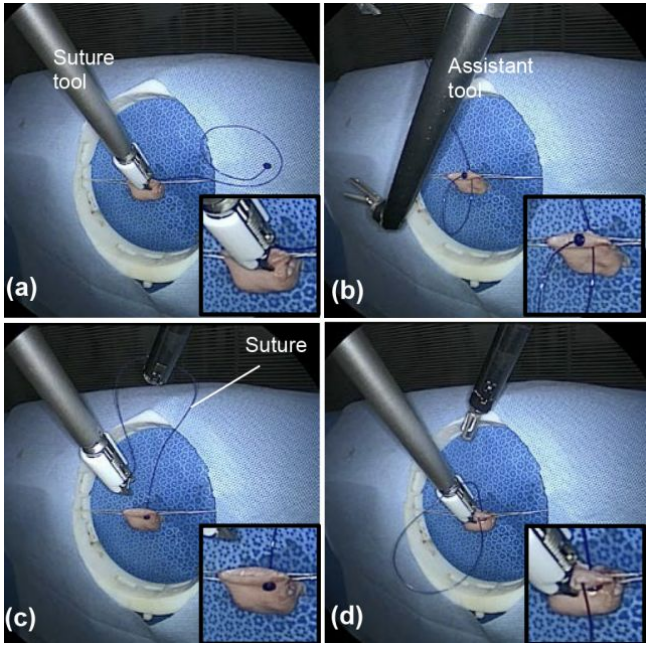
Mentors: Prof. Axel Krieger, PhD. Candidate Michael Kam

Summary of CIS2 Project



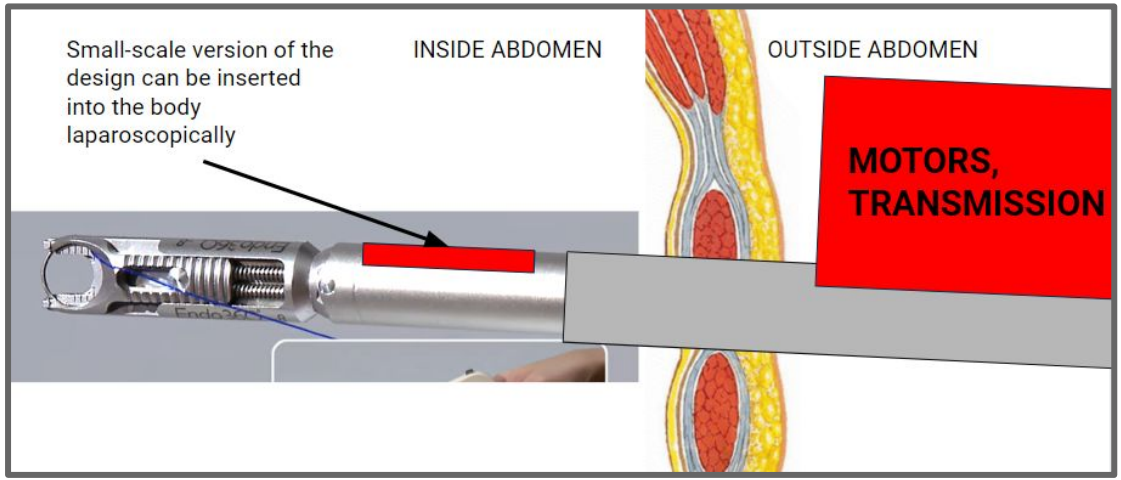


Diagram of our project goal

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

Selected Literature

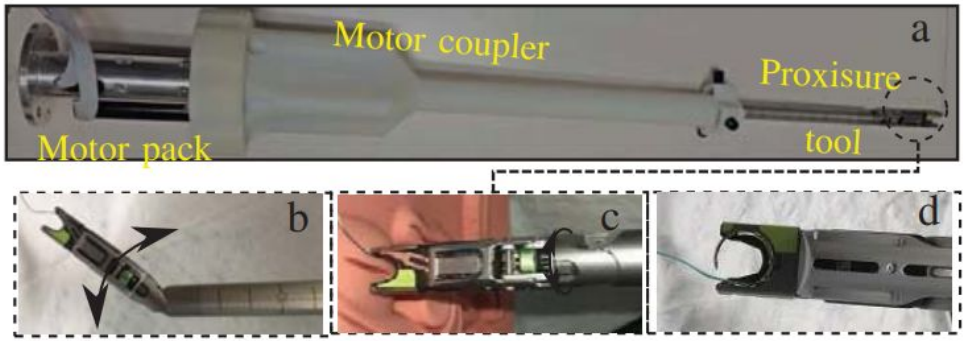
[1] H. Saeidi et al., "Autonomous Laparoscopic Robotic Suturing with a Novel Actuated Suturing Tool and 3D Endoscope," 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 1541-1547, doi: https://doi.org/10.1109/ICRA.2019.8794306.

[2] 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

Paper #1 Relevance

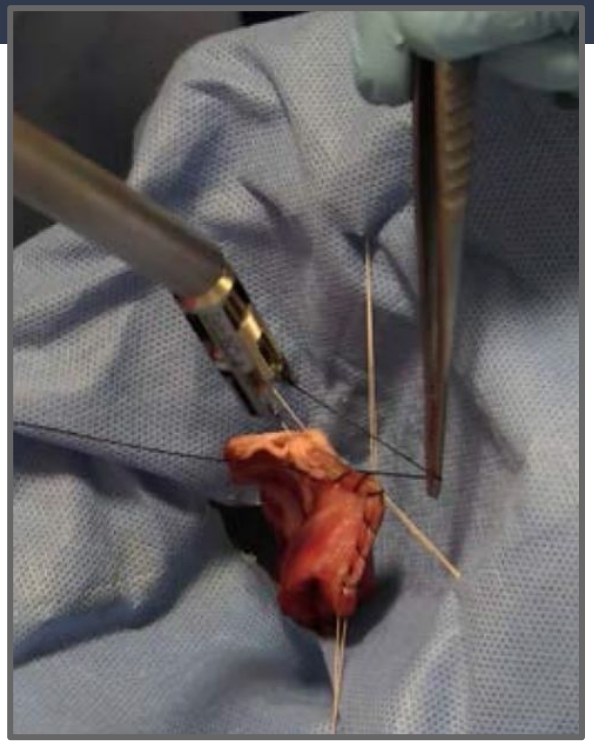
H. Saeidi et al., "Autonomous Laparoscopic Robotic Suturing with a Novel Actuated Suturing Tool and 3D Endoscope," 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 1541-1547, doi: https://doi.org/10.1109/ICRA.2019.8794306

- Evaluates the current highest DoA STAR system for laparoscopic workspace.
- Describes the design of the novel multi-axis autonomous suturing tool end effector (6 DOF) which our device will interface with.
- Discusses test results which we can use to compare the performance of STAR with our tensioning management system.



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

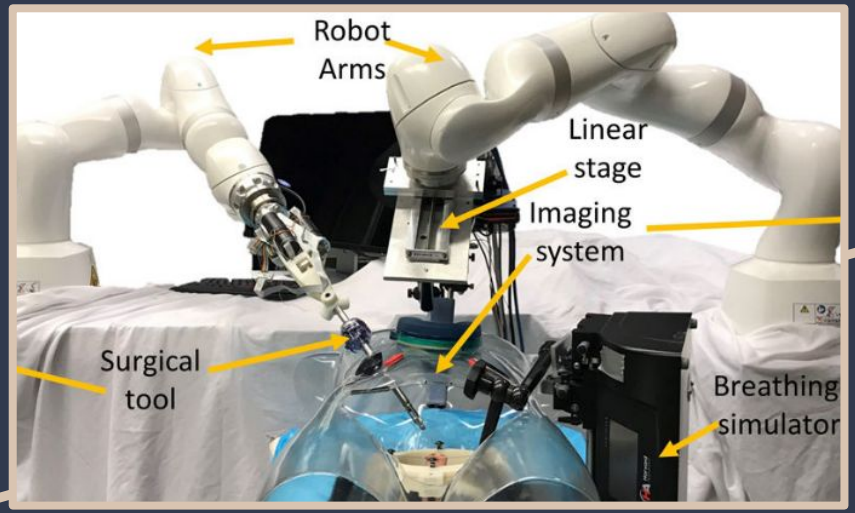
Paper Intro & Background summary



- Manual suturing in laparoscopic surgeries is time-consuming and inconsistent.
- This paper evaluates the performance of the STAR robot with a manually-controlled second arm. This was compared to the performance of manual laparoscopic surgery.

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

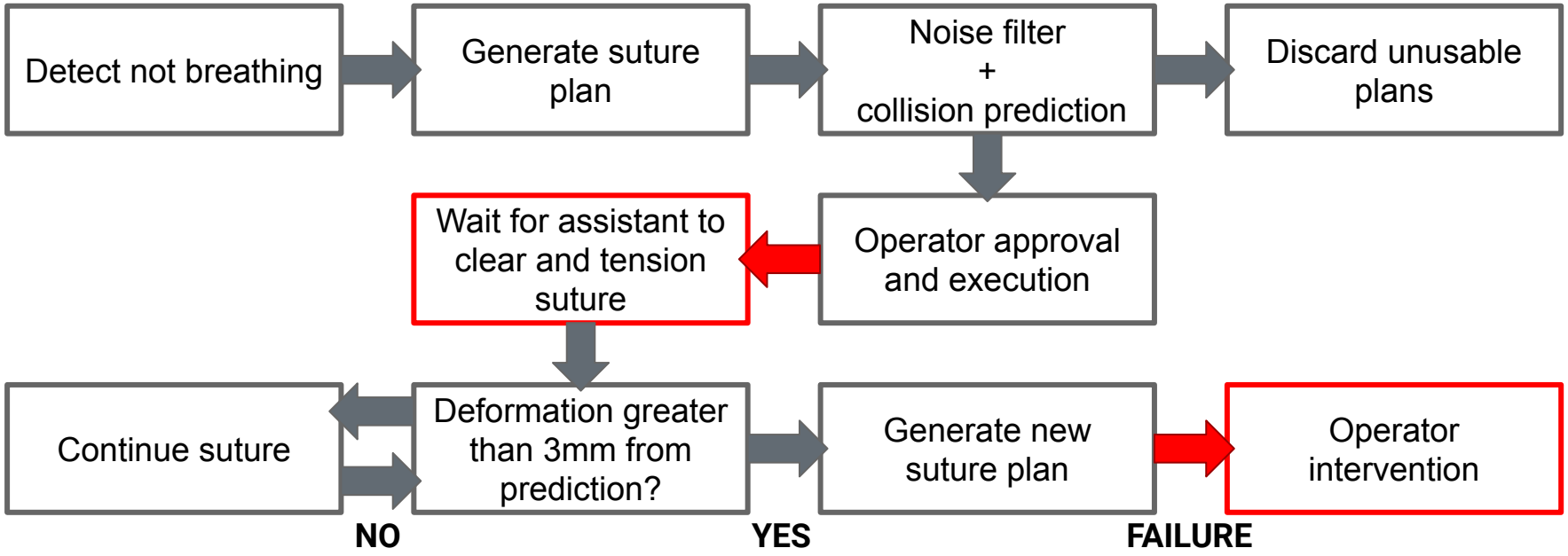
Methods: Setup



- 2 KUKA arms
  - 1 for suturing end effector
  - 1 for imaging system
- Imaging system
  - NIR camera
  - 3D mono color endoscope
- Phantom / in-vivo porcine small bowel
  - With NIR markers
  - 3D reconstruction of tissue

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

Methods: STAR Workflow



Results

- Average task completion time is 106.4 seconds longer for STAR than manual
- Variance of STAR spacing is significantly less. STAR is able to place sutures 2.9 times more consistently. Improved outcome [3, 4, 5].

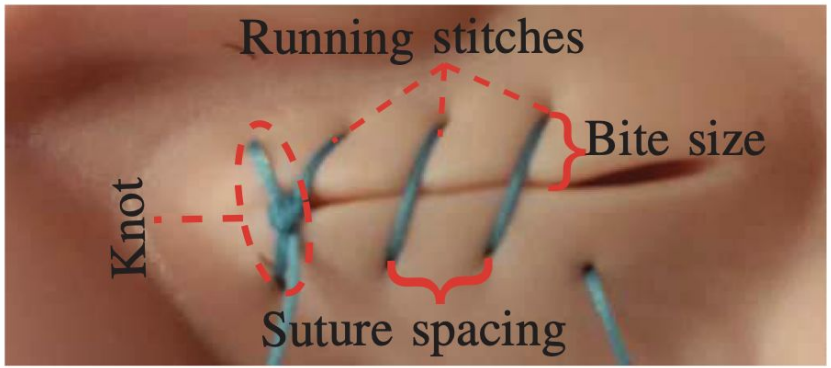


TABLE I: Comparison of the results via completion time.

	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

TABLE II: Comparison of the results via distance between stitches, bite size, and number of suture repositioning.

	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

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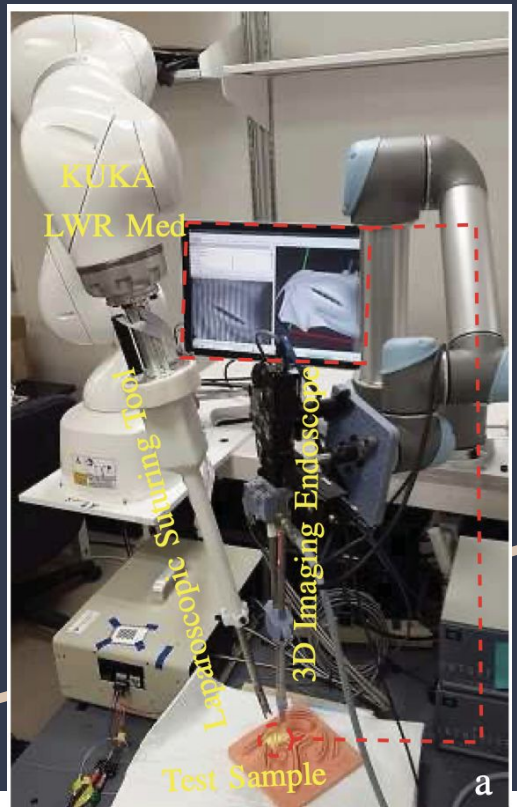
Critical Review



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Pros

- Explains the novel end effector hardware well.
- Testing and statistical analysis that we can use to compare the efficacy of our design.

Cons

- The STAR and surgeons only performed 3 stitches which is not enough to adequately assess variance in distance between stitches.
- Only evaluated performance against manual surgery not teleoperated RAS.
- Manual suturing was only performed by two different surgeons (small sample size).

Key Lessons

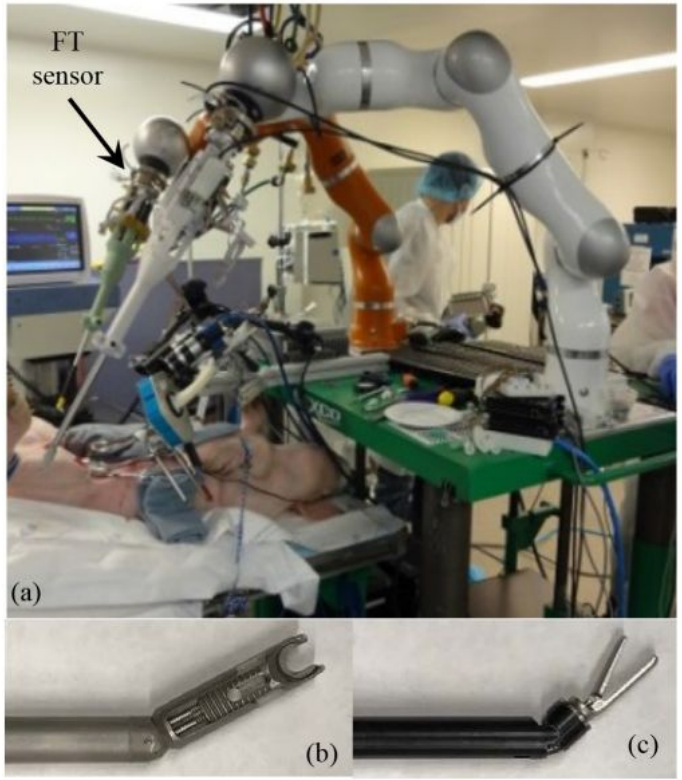
- Consistency and accuracy of suture placement in STAR outperforms manual surgery.
  - For our project: validates that putting more work into improving the STAR robot is worthwhile.
- STAR approach completion time is 106.4 seconds longer than manual.
  - For our project: decreasing the time per stitch will be a focus of our design.
- Discusses test results including time per stitch, distance between stitches, and bite size.
  - For our project: Use these metrics to compare the performance of STAR with our tensioning management system.

Paper #2 Relevance

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

- Evaluates current highest degree of autonomy STAR system (DoA 5).
  - Reveals flaws in the current system which we will address in our work.
- Shows STAR suturing robot workflow, outlining the tasks which our tensioning device must perform.
  - This contributes to our design requirements.
- Discusses testing and results which we can use to compare the efficacy of our device to the current highest DoA STAR system.

Paper Intro & Background summary



- Previous publications have shown that STAR is able to outperform human surgeons on anastomosis procedures.
- Goal: replace the need for a human assistant with the use of a second autonomous robotic arm to increase the level of autonomy of STAR.

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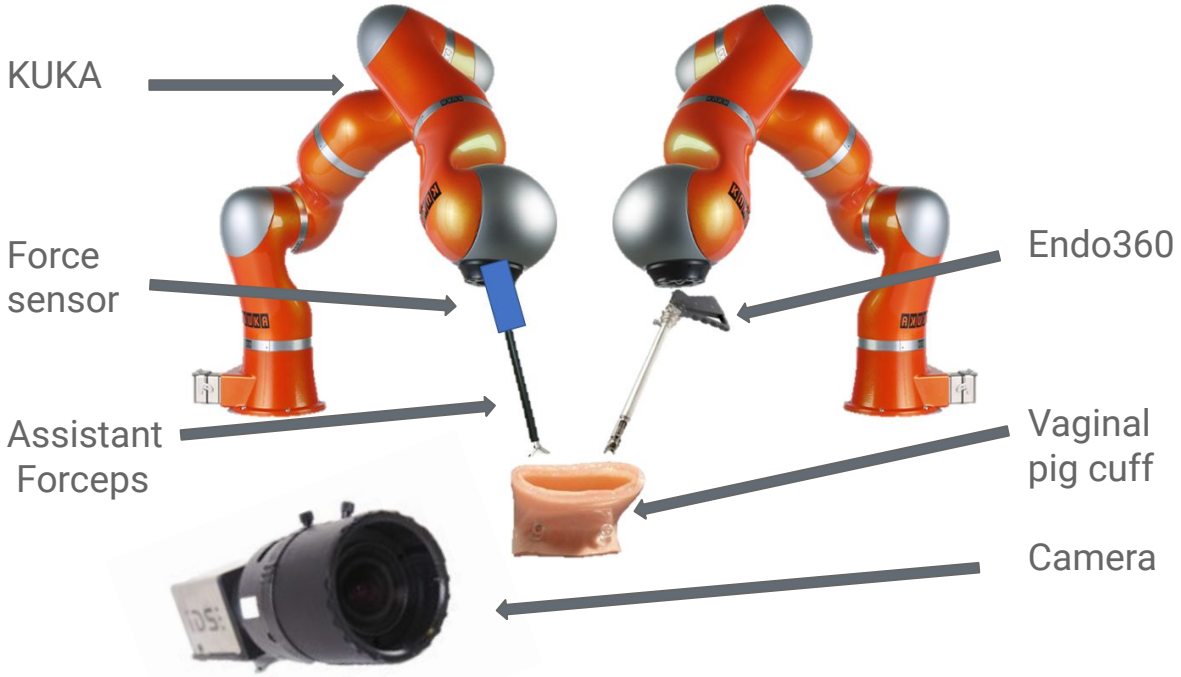
Methods: Setup

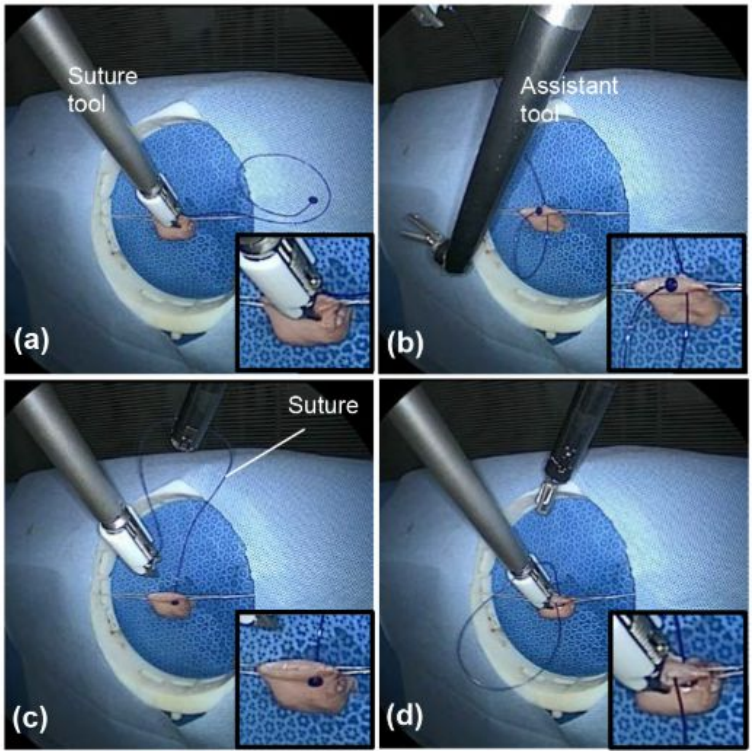
- Comparison between STAR (human/robot assistance), RAS and LAP
- Suturing vaginal cuff ex-vivo
- Sutures coated with NIRF for computer vision algorithm

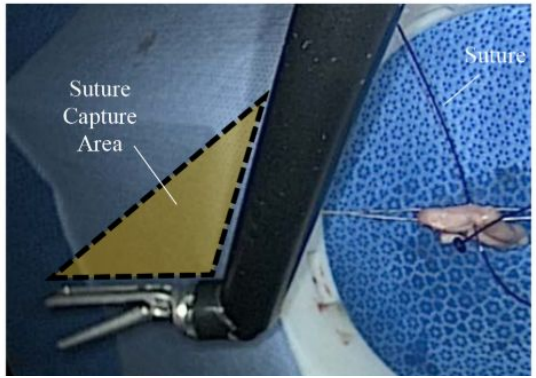


https://www.kuka.com
https://www.corporis-medical.com/product-page/reusable-laparoscopic-suturing-device-374mm/
https://www.3-dmed.com/product/vaginal-cuff-sample-pack-2-vaginal-cuff-small-mounting-pad/
https://www.intuitive.com/en-us/products-and-services/da-vinci/instruments
https://www.avgear.com/product/ids-ui-5240cp-nir-gige-camera-resolution-area-scan-camera-w-tamron-4-0-12mm-1-2-cctv-ir-lens/

Methods: Tool Manoeuvring

- Apply stitch [suture]
- Prepare tension [assistant]
  - Suture segmentation
  - Assistant capture formation
- Tension stitch [assistant]
  - Moves across workspace
  - Force sensor 5N
- Release [assistant]





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Results

- Automatic STAR has improved speed over LAP and RAS and reduced # of mistakes
- STAR has improved spacing variance

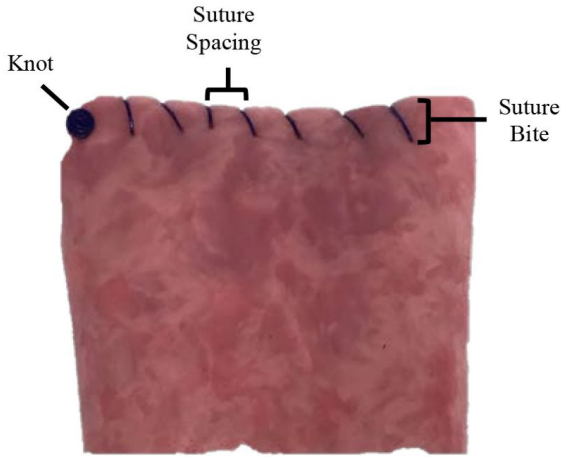

TABLE I
EX-VIVO VAGINAL CUFF CLOSURE

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

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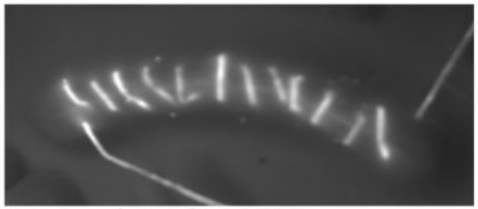
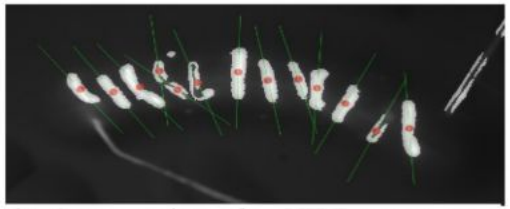
Critical Review

- Pros
  - Dual-arm STAR system has reached a DoA level of 5
  - Explains the force/torque sensor-based tensioning decision well.
- Cons
  - STAR Robot workspace is too large to operate laparoscopically. Just because NIRF-based CV works well in open space does not mean it will work well in a laparoscopic environment.
  - N=6 for each of the 3 classes (STAR, LAP, RAS) is not enough for good statistics.



(a) Imaging of a NIRF suture on a suturing pad.



(b) Segmentation of a NIRF suture on a suturing pad. The centroid and the main axis of each stitch is illustrated by a red dot and a green line respectively.

(c) 3D point cloud associated with each stitch. Distances between stitches can be measured by the centroids of adjacent boxes.

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Key Lessons

- Flaws with current design:
  - Workspace is currently too large to perform laparoscopic surgery with autonomous tension management.
  - Reliance on unnecessary complicated computer vision and control algorithms.
- Force/Torque sensor-based tensioning works well.
  - Experimental data is available as reference data for subsequent development

References

1. 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
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