Force-based Robot Learning from Demonstration for Soft Tissue Manipulation

Alaa Eldin Abdelaal[1], Jiaying Fang[2], Tim N. Reinhart[3], Jacob A. Mejia[3], Tony Z. Zhao[3], Chelsea Finn[3], Jeannette Bohg[3], and Allison M. Okamura[1]
Departments of [1]Mechanical Engineering, [2]Electrical Engineering, and [3]Computer Science
Stanford University

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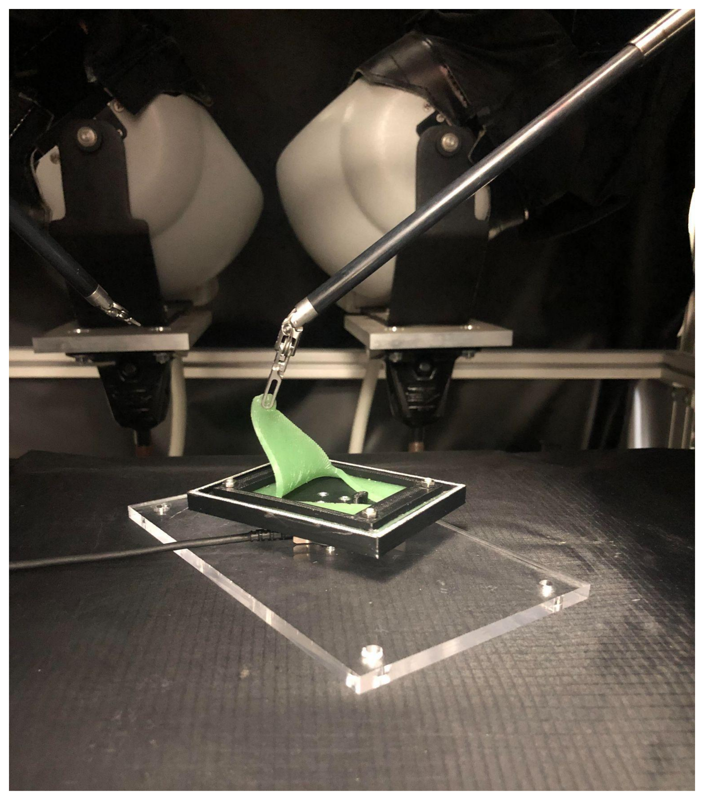
Introduction

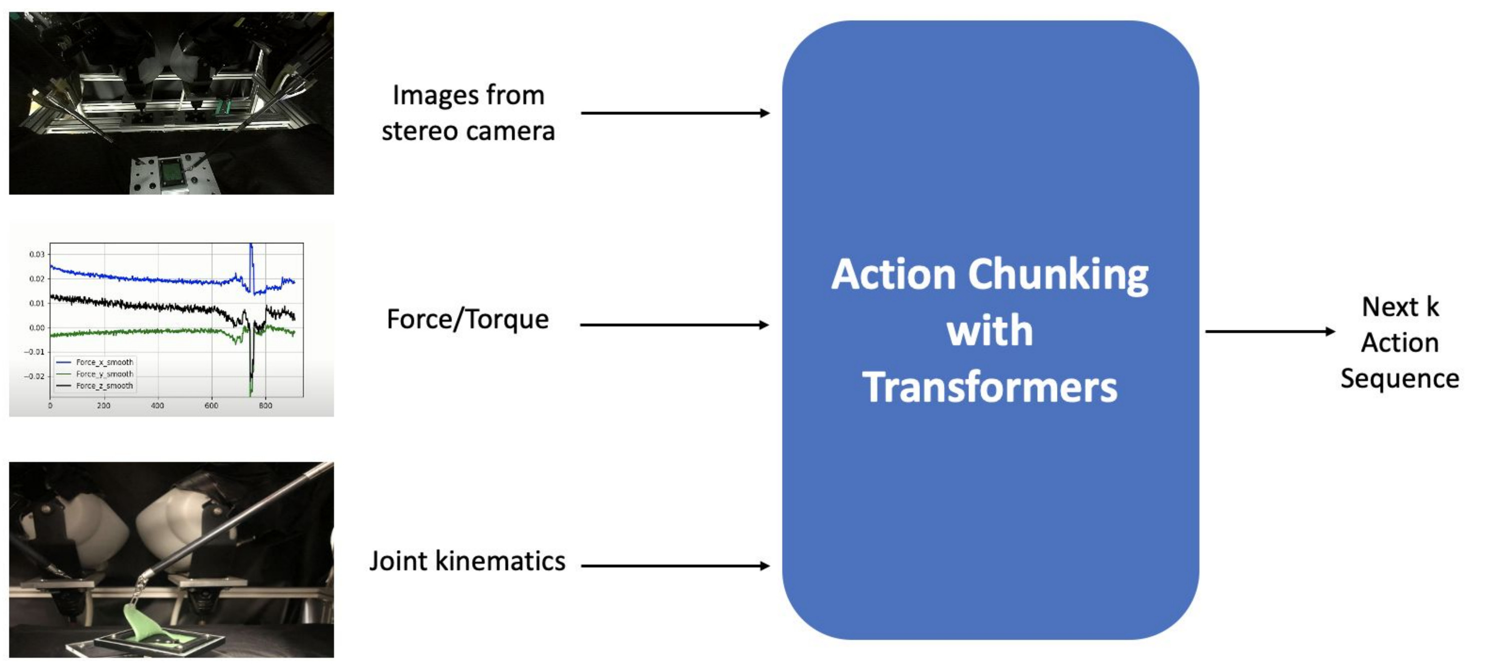
This work addresses the global shortage of surgeons and high rate of medical errors in the operating room by developing autonomous systems for robot-assisted surgery (RAS) to **augment the skills of human surgeons**. Despite the success of RAS, with millions of procedures performed every year, challenges remain in part due to the cognitive load on surgeons managing multiple robotic arms in existing RAS platforms (right). This work develops force-aware autonomous systems to handle the tasks of an additional robotic arm, such as tissue retraction, to reduce the surgeon's cognitive load and minimize negative outcomes. **We hypothesize that force-aware autonomous systems will have higher success rate and be more gentle with tissue in tasks requiring physical interaction, compared to force-agnostic ones**.

Methods



Imitation learning is used to automate tissue retraction, which is grasping a tissue sample to uncover the area underneath it. The system learns from human expert demonstration data collected using teleoperation. 60 demonstrations were collected using a research version of the **da Vinci Surgical System** (Intuitive Surgical, Inc.). The task set up is shown at right. A stereo camera views the scene and provides vision data for the learning process. A 6-axis force/torque sensor is mounted under the tissue to provide the force data used for training the imitation learning algorithm. The robot’s joint angles were directly collected from the da Vinci.

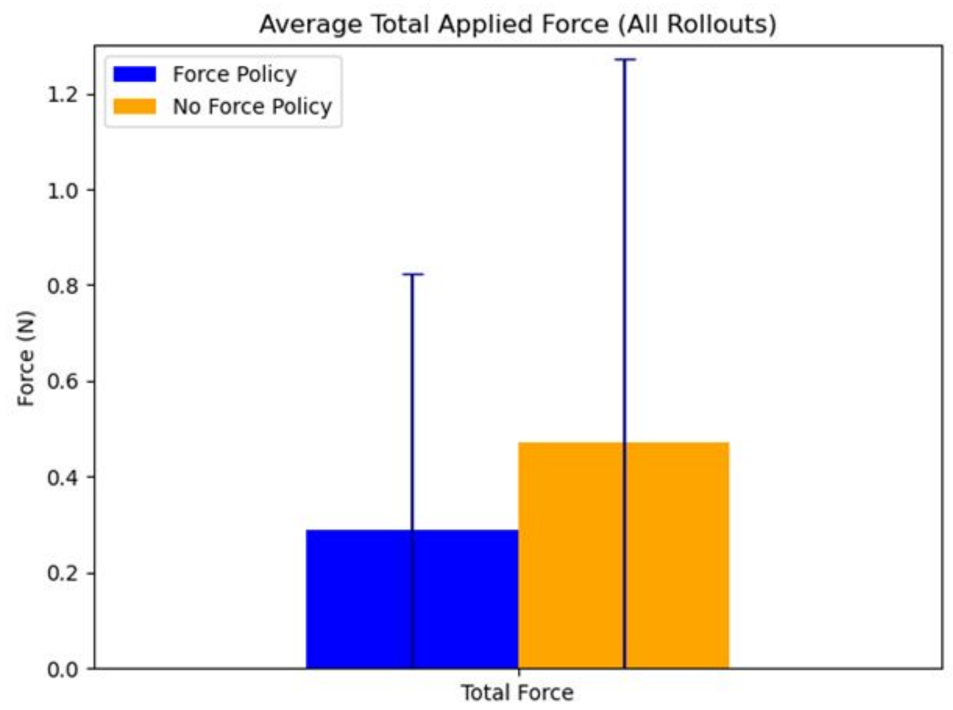
The imitation learning architecture is Action Chunking with Transformers (ACT) proposed by Zhao et al*. The inputs are images from the stereo camera, smoothed force/torque signal and robot joint angles, as shown below. To reduce the task horizon and compounding errors, the output of this network is the joint angles of the robot in the next k time steps. To quantify the effect of force/torque data, we trained and compared a “**no force policy**” that uses the vision and robot data and a “**force policy**” that uses force, vision and robot data.

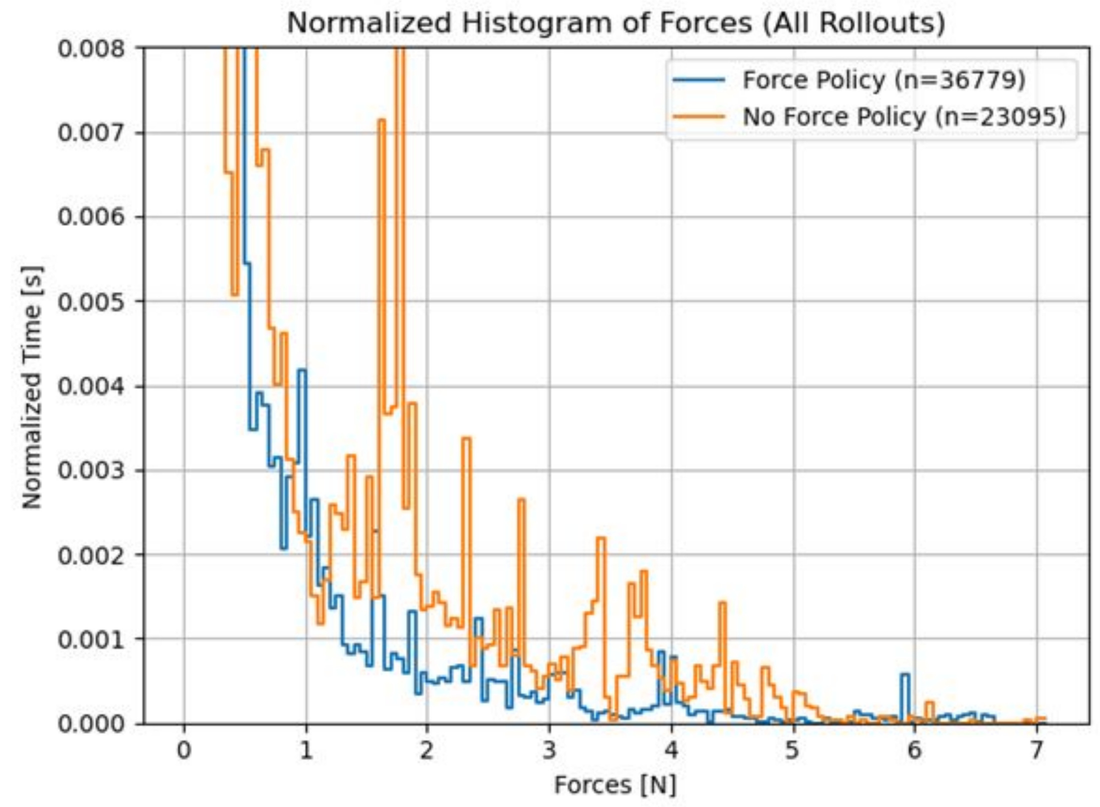


* T. Z. Zhao, V. Kumar, S. Levine, and C. Finn, “Learning Fine-Grained Bimanual Manipulation with Low-Cost Hardware,” *in Proc. of Robotics: Science and Systems*, Daegu, Korea, July 2023.

Results

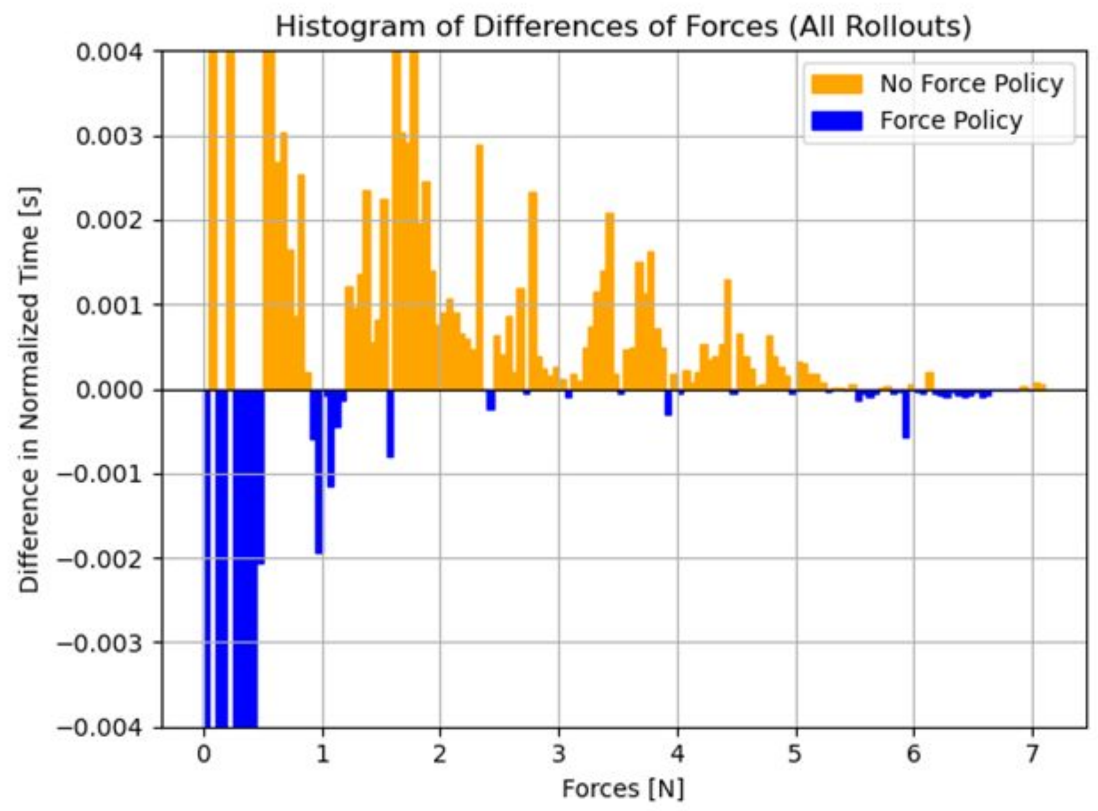
Over 50 roll outs of each policy, the force policy was successful 76% of the time and the no force policy was successful only 26% of the time. The no force policy applies 62% more force on average than the force policy, as shown at right. This suggests that **the application of force is smoother and more consistent when force data is utilized.**





The force policy demonstrates a steeper decline in the duration of force application as the force value increases, indicating a **more delicate and controlled interaction with tissue**. The plot at left shows the distribution of duration for which different forces were applied during the policy rollouts.

Moreover, the no force policy applies large forces more often. The figure at right shows the difference in amount of time a given force is applied. If all bars in the plot were orange, the no force policy would apply every given force more often than the force policy. The bars are predominantly orange for forces larger than 1N, so the **force policy is more gentle**.



Conclusion and Future Work

Force-aware autonomous systems have higher success rate and are more gentle with tissue compared with force-agnostic ones in an RAS manipulation task. Future work includes (i) estimating the force exerted by robotic manipulators based on robot state and vision data, instead of using force sensors, and (ii) exploring collaborative tasks between autonomous manipulators and teleoperated ones.

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