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From Theory to Practice: A Hands-On Laboratory Curriculum for Graduate Medical Robotics Education

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Abstract:

Medical robotics is a fast-evolving field that demands engineers with expertise in control, sensing, and human–robot interaction in safety-critical clinical contexts. To prepare students for these challenges, we developed a new graduate course at the University of Michigan that combines lectures, student-led discussions of current research, hands-on experiential laboratory sequence, and a student-chosen final project. This paper describes the design and evaluation of these labs, which guide students from manual surgical skills to robot-assisted and haptically-controlled procedures. Through the semester, students complete labs with topics on: (1) **suturing** on simulated tissue pads, (2) **laparoscopic and robotic surgery** using Fundamentals of Laparoscopic Surgery trainers and the da Vinci Surgical System simulator, (3) **robotic medical teleoperation** on a custom low-cost 1-DoF bilateral system, and (4) **virtual fixtures and haptics** using a 6-DoF force-feedback device to design and program constraints that guide a tool's motion in simulated surgical tasks. We assessed learning outcomes through pre- and post-lab surveys and reflective reports. Results indicate that the majority of students developed deeper understanding and greater confidence in both technical implementation and surgical task analysis. By releasing the lab hardware and software as open-source resources, this course offers a practical and adaptable framework for experiential medical robotics education that connects foundational theory to authentic clinical applications.

1 Introduction

Medical robotics has transformed the landscape of modern healthcare, introducing systems that enhance surgical precision, enable minimally invasive procedures, reduce patient recovery times, and facilitate remote care delivery. From the da Vinci Surgical System to emerging platforms for orthopedic surgery, microsurgery, and rehabilitation [1][2], robots have become integral in contemporary clinical practice. However, training engineers to design, implement, and evaluate these sophisticated systems requires an experiential approach that bridges the considerable gap between theoretical control systems education and the complex, safety-critical reality of the operating room. Traditional engineering curricula often isolate control theory, mechanical design, and human-robot interaction into separate courses, leaving students with fragmented understanding and limited intuition for the physical and cognitive constraints inherent to surgical environments, such as how tissue behaves under manipulation, how surgeons interact with robotic interfaces, or why certain design decisions matter in life-or-death contexts.

To address this need, the University of Michigan Robotics Department established a graduate-level course, Medical Robotics (ROB 599 - Special Topics in Robotics), designed to provide a comprehensive survey of medical robotics from an engineering perspective. The course was initially piloted in Winter 2023 as “Concepts in Medical Robotics”, focusing primarily on literature review and student-led discussions. This early iteration emphasized the breadth of medical robotics applications when students read scholarly papers and attended discussions on topics ranging from teleoperation and haptics to surgical imaging, safety systems, and regulatory pathways. While this seminar-based format provided valuable exposure to research frontiers, students entering the medical robotics workforce require hands-on experience to connect abstract concepts to concrete engineering decisions.

Recognizing the need for experiential learning, the curriculum was significantly expanded for the Winter 2025 iteration to include a dedicated laboratory sequence. This evolution shifted the teaching model to a “Learn-Reinforce-Integrate” approach: students learn concepts in lectures, reinforce them through hands-on labs, and integrate understanding through reflective assessments. The current iteration integrates four laboratories that progressively increase in technical complexity, guiding students from the user perspective (as surgeons) to the designer perspective (as engineers implementing control algorithms).

This paper presents the design and preliminary evaluation of this four-part laboratory sequence. Contributions include: (1) detailed descriptions of each laboratory module that other institutions may adapt; (2) assessment methodology combining surveys and qualitative reflections; (3) preliminary results on student learning outcomes; and (4) recommendations for implementation. The custom hardware and software are released as open-source resources.

2 Course Overview

Medical Robotics (ROB 599) is structured as a graduate-level survey meeting twice weekly for 80-minute sessions combining lectures and group discussions. The course is open to graduate students from robotics, mechanical engineering, electrical engineering, and biomedical engineering, with a target enrollment of 30 students.

The semester is divided into two phases. The first half covers engineering fundamentals: medical robot system architecture, manipulation (tooling, compliance, ports), control (teleoperation, force/impedance, virtual fixtures), and imaging integration. The second half focuses on clinical applications: minimally-invasive surgery, orthopedics, endoscopic interventions, rehabilitation, and advanced actuation. Assessment comprises literature discussion participation (20%), the laboratory sequence (30%), and a final design project (50%). The laboratory component is divided between individual reflective reports (20%) and team technical deliverables (10%). The weekly schedule for this course is outlined in Table 1.

3 Laboratory Curriculum

The laboratory curriculum was designed to ground theoretical concepts in physical reality and to guide students through a progression from manual surgical skills to advanced robotic control.

The sequence consists of four labs, each building upon the previous to transition students from the user perspective (experiencing surgery as surgeons do) to the designer perspective (implementing control algorithms as engineers do). This progression ensures that when students eventually write code for teleoperation and haptics, they possess the necessary understanding of surgical tasks to make informed design decisions.

Table 1: Weekly schedule of lecture topics and corresponding lab activities

Week	Lecture	Date	Unit	Class Topic	Paper Presentation	Assignments Due
1	Lec-01	Wed, Jan 08	Basics	Course overview, historical perspective, healthcare environments		
2	Lec-02	Mon, Jan 13	Basics	Medical robot systems, roles for robots		
	Lec-03	Wed, Jan 15	Basics	Essential human anatomy and physiology		Paper Team Sign-ups
3		Mon, Jan 20		**University Symposia - No Class**		
	Lec-04	Wed, Jan 22	Foundations	Manipulation: Tooling and access (ports)	Team 1	
4	Lec-05	Mon, Jan 27	Foundations	Manipulation: Tubular structures, steerable catheters/needles	Team 2	
		Wed, Jan 29		Guest Lecture: Medical robot design and risk management	Team 3	
5		Mon, Feb 03	Lab	Lab 1: Suturing		
	Lec-06	Wed, Feb 05	Foundations	Control: Force control, compliance	Team 4	
6	Lec-07	Mon, Feb 10	Foundations	Control: Teleoperation, latency, virtual fixtures	Team 5	Lab 1 Due
	Lec-08	Wed, Feb 12	Foundations	Imaging	Team 6	
7	Lec-09	Mon, Feb 17	Foundations	Human-robot interaction and safety	Team 7	
	Lec-10	Wed, Feb 19	Foundations	Levels of evidence, interpreting medical literature	Team 8	
8		Mon, Feb 24	Lab	Lab 2: CSC / Open Project OH		
		Wed, Feb 26	Lab	Lab 2: CSC / Open Project OH		Fri 2/28: Project Proposal
		Mon, Mar 03		**Winter Vacation - No Class**		
		Wed, Mar 05		**Winter Vacation - No Class**		
9		Mon, Mar 10	Lab	Lab 3: Teleoperation		Lab 2 Due
		Wed, Mar 12	Lab	Lab 3: Force feedback		
10	Lec-11	Mon, Mar 17	Applications	Minimally-invasive surgery	Team 9	
		Wed, Mar 19		Guest Lecture: Medical device regulation, licensing, commercialization		
11	Lec-12	Mon, Mar 24	Applications	Orthopedics	Team 10	Lab 3 Due
	Lec-13	Wed, Mar 26	Applications	Endoscopic, pill, and magnetic robots	Team 11	
12		Mon, Mar 31	Lab	Lab 4: Virtual Fixtures		Interim Report
		Wed, Apr 02	Lab	Lab 4: Virtual Fixtures		
13		Mon, Apr 07		**Project Office Hours**	Team 12	
		Wed, Apr 09	Lab	Lab 4: Virtual Fixtures		Fri 4/11: Lab 4 Due
14	Lec-14	Mon, Apr 14	Applications	Nursing, personal care, rehabilitation	Team 13	
	Lec-15	Wed, Apr 16	Applications	Autonomy / Advanced Actuation	Team 15	
15		Mon, Apr 21		**Final presentations + demos**		Final Presentation
		Mon, Apr 28		*No class... Reports Due ------>*		Final Report

3.1 Lab 1: Suturing on Simulated Tissue

Before designing robots to perform surgery, engineers must understand the complexity of manual tasks they intend to augment. Lab 1 introduces basic suturing techniques to establish appreciation for the dexterity, coordination, and multimodal sensory feedback required in open surgery.

3.1.1 Learning Objectives

1. Learn basic suturing techniques, including needle driving and instrument knot tying.
2. Understand the importance of visual, auditory, and tactile feedback in surgical tasks.
3. Understand the common tools and techniques employed in basic surgical procedures.
4. Develop foundational understanding to motivate subsequent labs in laparoscopic and robotic surgery.

By completing this lab, students gain firsthand appreciation for the cognitive and motor demands of surgical manipulation, which directly informs their later analysis of how robotic systems might address or introduce challenges in these tasks.

3.1.2 Hardware and Software Implementation

The lab utilizes standard off-the-shelf surgical training equipment (Figure 1). Suture pads are multi-layer silicone constructions simulating human skin with distinct epidermis, dermis, and subcutaneous tissue layers and a series of pre-created wounds. Many incorporate mesh within the dermis mimicking fascial layers. Standard surgical instrument kits contain needle drivers, graspers (forceps), and scissors. Students work with both braided sutures (better knot security, more tissue drag) and monofilament sutures (smoother tissue passage, requires more throws), experiencing how material properties affect technique.

Figure 1: Suturing lab instructor demonstration

3.1.3 Lab Protocol

Students form groups of three or four and obtain suture kits containing a suture pad, sutures of both types, needle drivers, graspers, and scissors. After identifying the nearest sharps disposal container for safety, students begin by examining the suture pad structure near a wound site to identify the distinct tissue layers and develop appreciation for the three-dimensional structure that sutures must traverse.

The procedure begins with simple interrupted sutures, the fundamental building block of wound closure. Each suture involves driving the needle through the epidermis on one side of the wound, passing through the subcutaneous tissue, exiting within the wound bed, then entering the wound on the opposite side and exiting through the epidermis. To conserve suture material, students pull through until approximately 5 cm of tail remains, then create a secure knot using the instrument tie technique—a skill requiring coordination between both hands and the needle driver. Finally, they trim excess suture leaving short tails of approximately 1 cm. This sequence is repeated with both braided and monofilament suture materials to highlight differences in handling characteristics and knot security.

Group members rotate while observing peers' techniques and considering how they might assist, such as preventing suture tangles or maintaining wound exposure. After everyone practices simple interrupted sutures, groups attempt advanced techniques including simple running sutures (a continuous line of stitches efficient for long wounds), vertical mattress sutures (providing eversion for improved wound edge approximation), and deep dermal sutures (burying knots beneath the skin surface for cosmetic closure). Throughout, students are explicitly tasked with analyzing the degrees of freedom required for the task and considering how absence of tactile feedback would alter difficulty—a direct primer for subsequent teleoperation labs.

3.2 Lab 2: Laparoscopic and Robotic Surgery

This lab demonstrates manual laparoscopic surgery and robot-assisted procedures by introducing Minimally Invasive Surgery (MIS). Students experience how separating the surgeon's hands from the surgical site fundamentally changes the task through both kinematic constraints of laparoscopic instruments and the interface of a robotic surgical system.

3.2.1 Learning Objectives

1. Compare and contrast laparoscopic and robotic manipulation across dexterity, precision, and sensory feedback.
2. Experience the “fulcrum effect” and reduced dexterity in laparoscopic surgery, where instruments pivot about the port creating inverted motion.
3. Evaluate tradeoffs between improved dexterity from articulated robotic instruments and loss of direct haptic feedback.
4. Analyze how camera placement affects task difficulty in image-guided surgery.

These objectives build directly on Lab 1 by allowing students to compare their fresh memory of open surgical manipulation against new constrained modalities.

3.2.2 Hardware and Software Implementation

The laparoscopic station uses Fundamentals of Laparoscopic Surgery (FLS) trainer boxes, a standard certification equipment containing a simulated abdominal cavity with ports and integrated camera system (Figure 2a). Standard laparoscopic graspers with lever handles and rotational control knobs allow manipulation while experiencing the characteristic long-shafted, non-articulated tool design.

The robotic surgery component uses a da Vinci Surgical System simulator replicating the surgeon console with master controllers, stereoscopic display, and foot pedal controls (Figure 2b). The simulator includes artificial haptic feedback approximating tissue manipulation forces, allowing discussion of how this differs from the force-free experience of actual clinical systems.

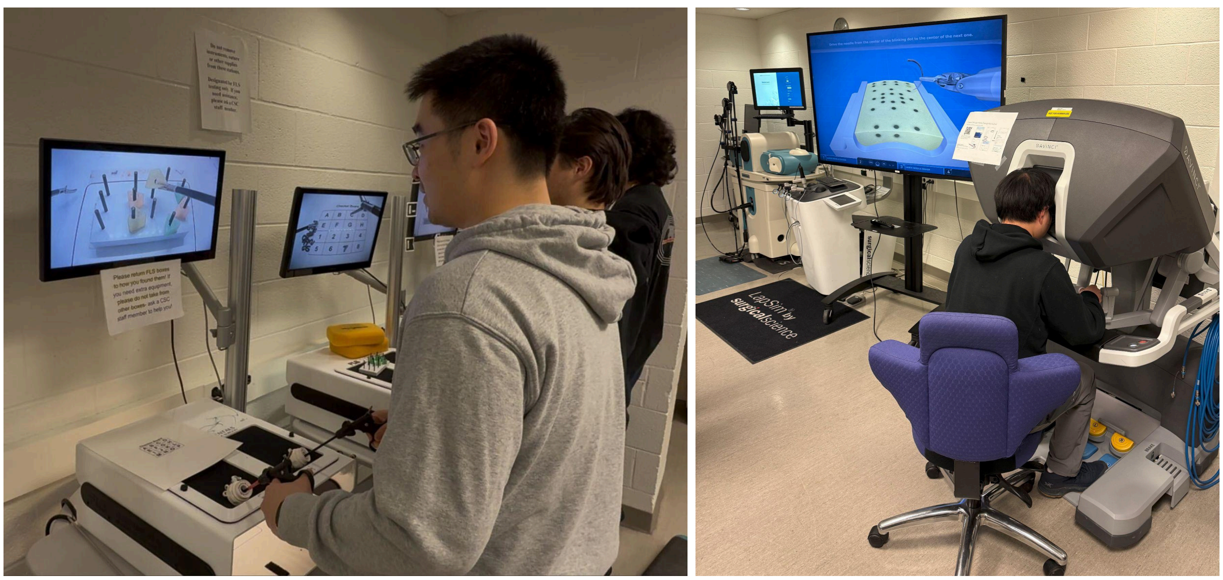

Figure 2: (a) Student using an FLS trainer and (b) student using the da Vinci simulator

3.2.3 Lab Protocol

The lab is organized into two 30-minute rotations with groups swapping between stations at the midpoint. In the laparoscopic rotation, students complete the peg transfer task, a timed assessment that is part of the standard FLS certification. This task requires transferring small triangular objects between pegs arranged in a specific pattern, using instruments inserted through ports. Students first familiarize themselves with the laparoscopic tool handles, including the lever mechanism for operating the grasper and the knob for rotating the tool shaft. They then complete peg transfer using a single instrument, experiencing the difficulty of precise manipulation with limited degrees of freedom, before attempting the task with two instruments. Friendly competition within groups for fastest completion times motivates engagement and provides immediate performance feedback.

In the robotic surgery rotation, students take turns at the da Vinci simulator console. They familiarize themselves with the surgeon console interface, including the "clutching" mechanism that allows repositioning the master controllers without moving the instruments, camera control for adjusting the surgical viewpoint, and operation of the articulated EndoWrist graspers that provide additional degrees of freedom at the instrument tip. Students complete ring transfer exercises similar to the laparoscopic peg transfer, allowing direct comparison of task performance. They also attempt suturing tasks of varying complexity, using the articulated wrist to overcome limitations they experienced with rigid laparoscopic tools. Throughout both rotations, students reflect on how each interface affects their perception of the surgical workspace, their confidence in manipulation, and their sense of presence at the task site.

3.3 Lab 3: Robotic Medical Teleoperation

In Lab 3, students transition from users of surgical systems to engineers who implement and tune control algorithms. Using a custom-designed 1-DoF bilateral teleoperation testbed, students gain hands-on experience with the fundamental challenges of creating a responsive, stable, and transparent leader-follower system. This lab focuses on the practical realities of teleoperation control, including the effects of controller tuning, nonlinearities like deadband and saturation, and the critical challenge of communication latency that affects remote surgical applications.

3.3.1 Learning Objectives

1. Implement proportional-derivative (PD) control for teleoperation position tracking.
2. Understand practical effects of deadband, saturation, and filtering on system performance.
3. Tune haptic feedback parameters to create "transparency" where operators perceive the remote environment.
4. Analyze how communication latency degrades performance and explore compensation strategies.

3.3.2 Hardware and Software Implementation

The custom teleoperation rig consists of two matched belt-driven linear actuators serving as leader and follower devices (Figure 3a). The leader features a handle that permits 1-DoF movement; the follower includes a needle probe for simulating surgical interaction. An adjustable-tension belt-drive transmission provides low backlash and high backdrivability on the leader (essential for haptic feedback) while the follower uses a higher gear ratio for increased force output.

The electronics platform centers on a Raspberry Pi Pico microcontroller on a customized MBot control board [3][4]. Motor encoders provide position and velocity measurements; PWM signals drive DC motors. The 12V battery provides portable, safe power. Students develop firmware in

C using the Pico SDK, compiling and flashing through USB, exposing them to embedded systems development workflows.

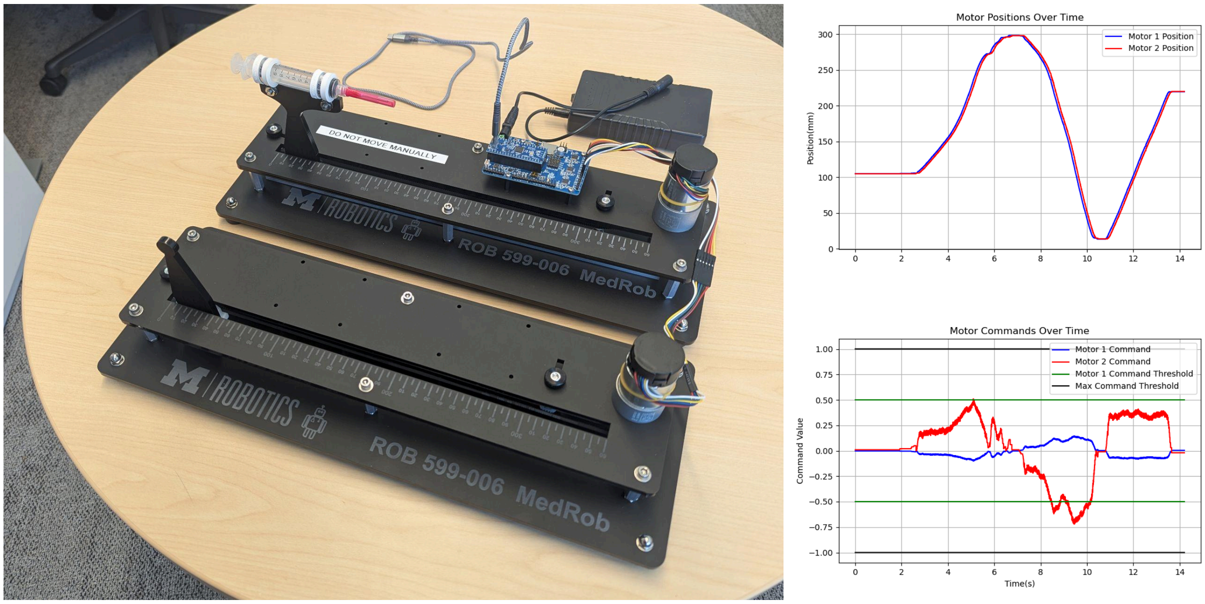

Figure 3: (a) Teleoperation setup showing leader and follower devices and (b) student submission plot showing successful position tracking

3.3.3 Lab Protocol

The lab spans two class periods to allow sufficient time for implementation, tuning, and experimentation. Students begin by setting up the hardware: securing the control board with all bolts, ensuring ribbon cables are properly connected, and checking belt tension on both devices. The leader should move freely while the follower (marked "DO NOT MOVE MANUALLY" in Figure 3a) should only be driven by the motor to protect the high-gear-ratio transmission.

The first phase focuses on tuning follower tracking. Starting from a PD controller template in C, teams adjust proportional and derivative gains to achieve responsive tracking without overshoot or oscillation. The workflow involves editing the control code in Visual Studio Code, compiling with the Pico SDK using make commands, putting the Pico in flash mode by pressing BOOTSEL and RST buttons simultaneously, and copying the compiled firmware file to the device. Students collect step response data by setting the leader to a known displacement and recording follower behavior, quantifying settling time, overshoot, and steady-state error across parameter sets (Figure 3b).

The second phase introduces haptic feedback on the leader device, rendering forces reflecting what the follower encounters. Students discover that naive high-gain feedback quickly leads to motor stall on the low-gear-ratio leader, requiring careful tuning. They implement deadband to reduce jitter at rest—ignoring haptic commands below a threshold error—accepting a small perceptual dead zone in exchange for stability. They implement saturation to protect motors from overheating while providing perceptual cues (such as vibration pulses) alerting operators when force limits are approached.

Advanced exercises include operating “remotely” using a cellphone camera on Zoom to view the follower while controlling from a separate location, introducing artificial communication delays (0-150 ms) simulating telesurgery scenarios, and implementing filtering or predictive compensation strategies. Students observe how latency degrades performance and must re-tune controllers to compensate. A competition challenges teams to achieve fastest needle positioning—approaching tissue paper within 5 mm without piercing—with extra credit awarded for the top three times. This gamification motivates optimization while highlighting practical control implications.

3.4 Lab 4: Virtual Fixtures and Haptics

The final lab explores advanced assistance via virtual fixtures, software-generated force constraints that guide or restrict an operator's motion to enhance safety and performance. Students progress from the 1-DoF system of Lab 3 to a commercial 6-DoF haptic device, implementing mathematical descriptions of force fields and experiencing how haptic feedback can implement sophisticated assistance strategies. This lab represents the culmination of the laboratory sequence, requiring integration of control theory, haptic rendering, and clinical problem-solving.

3.4.1 Learning Objectives

1. Understand how haptic feedback implements virtual fixtures including guidance constraints and forbidden regions.
2. Write mathematical and software descriptions of haptic feedback including springs, dampers, and friction.
3. Design and implement virtual fixtures for complex surgical tasks combining multiple constraint types.
4. Analyze limitations from force magnitude, rendering stability, and perceptual fidelity.

3.4.2 Hardware and Software Implementation

The lab utilizes Geomagic Touch devices from 3D Systems [5]. These commercial haptic interfaces provide 6-DoF position and velocity sensing of a stylus-style end effector with 3-DoF force feedback (Figure 4a). The device runs a 1 kHz control loop with the host PC, providing the high update rates necessary for stable and realistic haptic rendering. The stylus form factor mimics a surgical instrument, making the interface intuitive for medical robotics applications.

The software environment combines a Panda3D-based visualization interface with C++ code for force rendering (haptics.cpp). The customized application provides real-time 3D visualization of the virtual workspace, constraint geometries, and tool position, while the C++ layer handles the mathematically intensive force calculations at the required update rate. Students modify the haptics.cpp file to implement various haptic effects, allowing them to focus on control algorithms rather than device driver details. Python scripts (main.py) provide additional data logging and analysis capabilities.

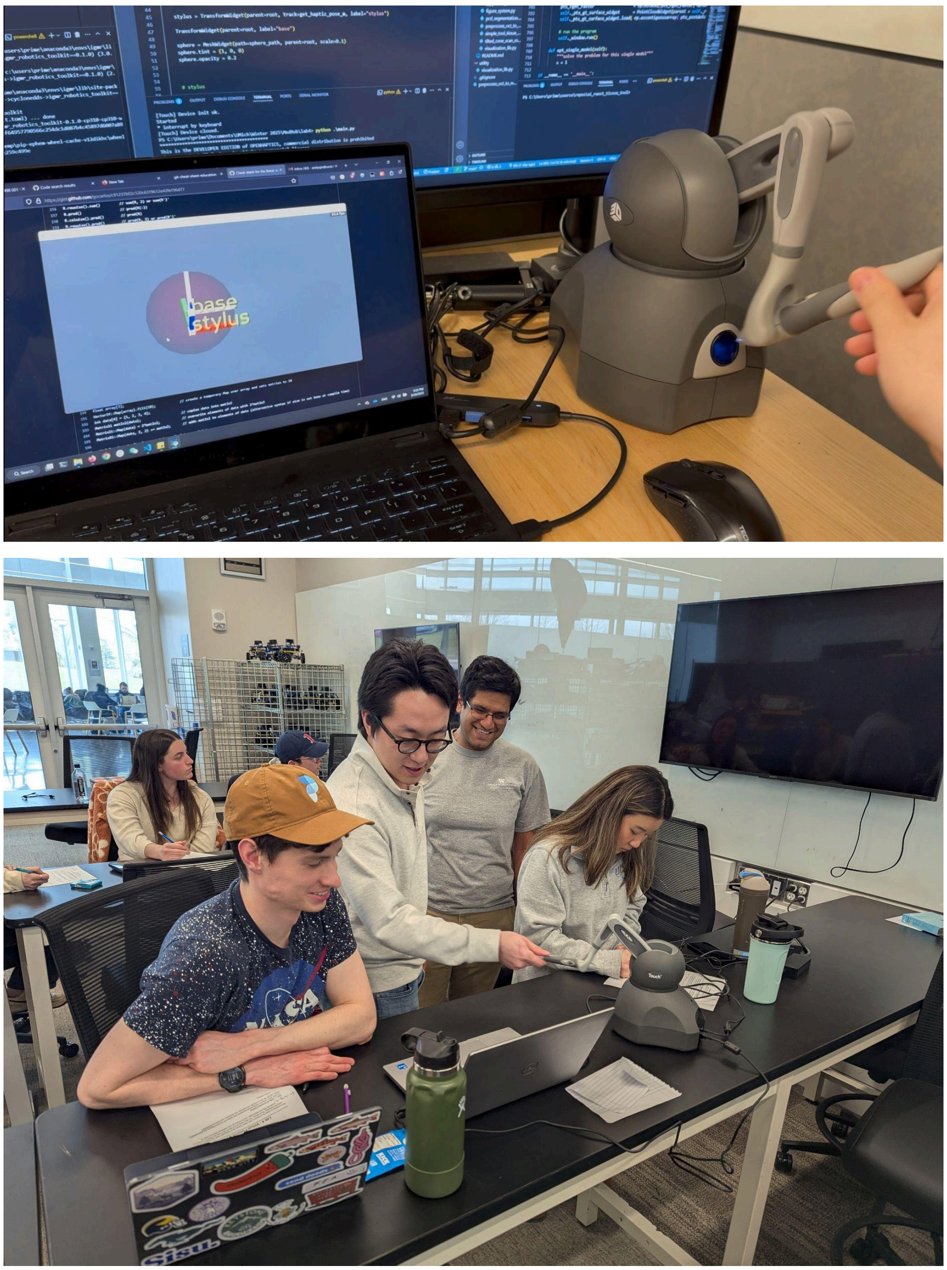

Figure 4: (a) Geomagic Touch haptic device in customized simulation and (b) students developing their own responses.

3.4.3 Lab Protocol

The lab begins with a Unity environment demonstration [6] where students experience pre-coded haptic effects before implementing their own. Demo scenarios include surface stiffness (feeling a virtual wall), viscous damping (moving through virtual fluid), surface friction (sliding resistance), lifting masses (gravity compensation), constant force fields, virtual springs (attraction to a point), and push-through forces (breaking through a membrane). For each effect, students work in teams to derive the mathematical expression relating rendered force to stylus position and/or velocity, building intuition for force feedback programming. Team members rotate access to the haptic device while others complete worksheets and discuss implementation strategies (Figure 4b).

In the implementation phase, students code their own haptic responses, progressing through virtual springs, solid spheres (forbidden region), solid cubes (axis-aligned forbidden region), viscous damping, surface friction, attract-to-line (guidance along a path), and attract-to-curve (guidance along a parametric trajectory). Each effect builds on previous implementations, creating a library of primitives that can be combined for complex fixtures. The progression from point attraction to line attraction to curve attraction illustrates how guidance constraints can be generalized across geometric primitives.

An optional application challenge invites teams to design haptic algorithms for specific medical procedures. One example scenario involves a robotic appendectomy with three surgical ports (one for camera, two for instruments). Teams must implement a haptic feedback sequence that guides an instrument to any port site without requiring visual focus, then assists advancement along the port axis once inside. The constraint regions for each port must not interfere with each other, and the system should automatically activate the appropriate guidance based on tool proximity rather than requiring explicit operator selection. This open-ended challenge encourages creative application of the haptic primitives to authentic clinical problems, generating diverse student solutions including catheter guidance systems and tumor resection assistance.

4 Assessment Methods

Student learning is assessed through quantitative surveys and qualitative reflective analysis.

4.1 Survey Design

Anonymous pre-lab and post-lab surveys administered through online forms capture changes in student self-reported confidence using a 5-point Likert scale (1=Strongly Disagree to 5=Strongly Agree). Survey items address both technical competencies (e.g., “I feel comfortable implementing PD control for a bilateral teleoperation system”) and broader professional preparation. Open-ended questions invite students to identify valuable aspects of each lab and suggest improvements. Appendix contains the complete survey questions used to assess students' confidence levels.

4.2 Reflective Reports

After each lab, students submit individual reflective reports synthesizing physical experience with theoretical concepts. For example, Lab 1 reflections ask students to analyze degrees of freedom required for suturing and predict how absence of tactile feedback would affect task difficulty. Lab 3 reflections address tuning strategies, observed effects of non-linearities, and latency compensation approaches. Reports are graded using rubrics assessing technical depth, connection to course concepts, and writing quality.

4.3 Technical Deliverables

For the programming-intensive Labs 3 and 4, teams submit technical deliverables including source code, performance plots, and demonstration videos. Code is evaluated for correctness, style, and documentation. Performance plots provide quantitative evidence of system behavior. Videos demonstrate functional operation, particularly for haptic implementations difficult to evaluate through code inspection.

5 Results

Student learning outcomes were assessed through surveys and discussions administered at the beginning and end of each laboratory session. For lab 3 and lab 4, surveys consisted of Likert-scale items aligned with specific learning objectives for each lab. 1=Strongly Disagree represents low confidence and 5=Strongly Agree means high confidence about a certain learning topic. Response distributions were visualized using 100% stacked bar charts (Figure 5) to compare self-efficacy beliefs before and after each lab. Lab 3 collected N_{pre}=23 and N_{post}=15 responses, while lab 4 collected N_{pre}=19 and N_{post}=11 responses. The variation in sample sizes was slightly due to attendance and response rate.

Pre-lab to post-lab comparisons revealed substantial gains in self-reported understanding and confidence across both technical laboratories. Lab 4 produced the largest improvements, particularly in implementation-focused skills. For the item assessing ability to implement a virtual fixture using haptic feedback, the mean confidence score increased by 1.91 points on the 5-point scale—from 2.00 (between Disagree and Neutral) to 3.91 (approaching Agree). Before the lab, 73.7% of students disagreed or strongly disagreed that they could implement a virtual fixture; after the lab, 90.9% agreed or strongly agreed. This dramatic shift suggests the hands-on implementation experience effectively bridges the gap between theoretical knowledge and practical capability [7].

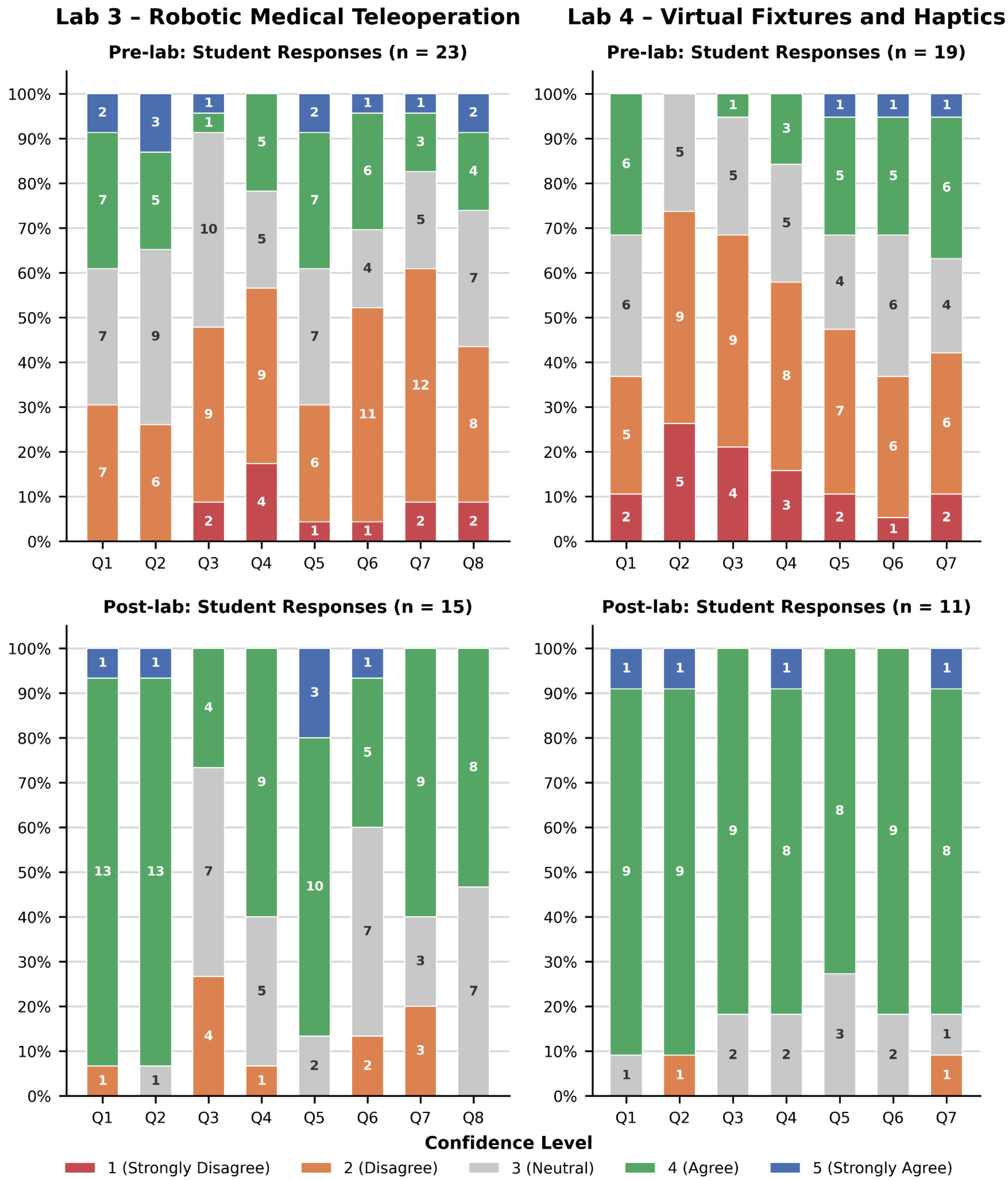

Figure 5: Stacked bar charts visualization of pre/post survey results for Lab 3 and 4

Table 2 below presents the complete pre/post survey results for both technical laboratories. For Lab 4, additional notable improvements included writing mathematical expressions for haptic force functions (+1.66, from 2.16 to 3.82) and writing corresponding computer code (+1.49, from 2.42 to 3.91). Students also gained confidence in describing common haptic feedback types (+1.16), recommending appropriate haptic feedback for clinical tasks (+0.94), and tuning haptic parameters (+0.92). For Lab 3, the strongest conceptual gain was in explaining the effects of deadband and backlash on control systems (+1.06, from 2.48 to 3.53). Students also showed improved understanding of latency effects in teleoperation (+0.94, from 3.13 to 4.07), and increased confidence in their PID tuning strategies (+0.76) and ability to diagnose poorly-tuned control systems (+0.78).

Table 2: Quantified pre/post survey confidence level for Lab 3 and 4

Lab 3 (Teleoperation)

#	Learning Objective	Pre	Post	Δ
Q1	PID tuning strategy	3.17	3.93	+0.76
Q2	Diagnose poorly tuned PID	3.22	4.00	+0.78
Q3	Implement tremor filtering	2.57	3.00	+0.43
Q4	Explain deadband and backlash	2.48	3.53	+1.06
Q5	Explain latency effects	3.13	4.07	+0.94
Q6	Implement force feedback algorithm	2.78	3.33	+0.55
Q7	Mitigate latency effects	2.52	3.40	+0.88
Q8	Design evaluation experiments	2.83	3.53	+0.71

Lab 4 (Haptics)

#	Learning Objective	Pre	Post	Δ
Q1	Describe common haptic feedback types	2.84	4.00	+1.16
Q2	Implement a virtual fixture	2.00	3.91	+1.91
Q3	Write mathematical expression for force	2.16	3.82	+1.66
Q4	Write computer code for force function	2.42	3.91	+1.49
Q5	Recommend appropriate haptic feedback	2.79	3.73	+0.94
Q6	Explain limits (strength/stability)	2.95	3.82	+0.87
Q7	Tune haptic parameters	2.89	3.82	+0.92

Reflective report analysis reveals several recurring themes. In Labs 1 and 2, students consistently report frustration with counter-intuitive laparoscopic motion due to the fulcrum effect, followed by appreciation for the da Vinci articulated wrist restoring natural hand-eye coordination. One student wrote: “After struggling to transfer a single peg with the laparoscopic tools, using the da Vinci felt like my hands had been returned to me.” This sequence of experiences generates compelling insights about why surgeons might prefer robotic systems despite losing direct haptic feedback.

For the technical labs, progression from 1-DoF to 6-DoF allows students to isolate control variables before confronting full spatial manipulation complexity. Reflections indicate that tuning the simplified system provided intuition for understanding complex force vectors in the virtual fixture lab. Many report moments when lecture concepts—such as the difference between position-position and position-force control architectures—suddenly made sense through direct system experience. Students also developed appreciation for practical engineering challenges: belt tensioning, motor thermal limits, and the difficulty of achieving both responsiveness and stability simultaneously.

The Lab 4 application challenge generated diverse creative solutions: virtual fixture designs for catheter guidance, haptic-assisted tumor resection, trocar insertion assistance, and needle biopsy guidance. The quality and creativity of these designs demonstrates students' ability to transfer core haptic primitives to authentic clinical problem-solving, representing a key learning objective of the laboratory sequence.

6 Discussion

The transition from seminar format to lab-integrated curriculum addresses a critical gap: physical intuition for safety and interaction that cannot be conveyed through equations alone [8]. By requiring students to manually suture (Lab 1) before encountering laparoscopic constraints (Lab 2), and implementing basic teleoperation (Lab 3) before programming virtual fixtures (Lab 4), engineering decisions are grounded in clinical reality.

The quantitative results support that hands-on laboratories effectively bridge theoretical knowledge and practical skills. The largest improvements occurred in skills that students had little opportunity to develop prior to the lab—particularly implementing virtual fixtures and writing haptic force functions. These findings align with self-efficacy research suggesting that mastery experiences are the most powerful source of efficacy beliefs [7]. Even students with prior control systems background reported meaningful improvements, indicating the medical robotics context provides value beyond generic controls education [9].

6.1 Challenges

A key challenge identified during the course offering is hardware reliability. The custom 1-DoF kits used in Lab 3 require significant maintenance, and pinch points, belt tension issues, or thermal limits of the motors can interrupt the learning flow. In several instances, hardware troubleshooting consumed time that was intended for control experimentation. Creating robust and duplicate lab kits, as recommended by similar laboratory-integrated courses, will be a priority for future iterations.

Software environment setup for Lab 3 also presented challenges. Students use a variety of operating systems (Windows, Mac, Linux), and the embedded development toolchain behaves differently across platforms. Pre-lab preparation materials helped, but some students still spent significant time troubleshooting compilation issues rather than focusing on control concepts. Future offerings will explore containerized development environments or cloud-based compilation services to reduce setup friction.

6.2 Recommendations for Implementation

Based on our experiences, we recommend the following practices for implementation of similar laboratory curricula:

1. Create robust and duplicate lab kits to mitigate hardware failures as having spare components available allows students to continue working while issues are resolved.
2. Develop comprehensive documentation for teaching staff to support consistency across lab sessions and instructors.

3. Thoroughly motivate and frame the laboratory sequence in early lectures so that students understand how each lab connects to broader course themes.
4. Track student perceptions longitudinally throughout their degree program, as the value of foundational experiences may only become apparent in later coursework.
5. Release lab materials as open-source resources to enable broader adoption and community improvement. We have made the software and documentation for Labs 3 and 4 available through public GitHub repositories, allowing other institutions to adapt and extend the curriculum [10].

6.3 Limitations

This study has limitations including a single course offering with modest sample sizes (15-23 students per survey), self-reported data potentially subject to response bias, and absence of a control group preventing direct causal attribution. The pre/post design cannot distinguish between learning from laboratories versus concurrent lecture material. Future work will incorporate standardized performance assessments to complement self-report measures.

7 Conclusion

This paper presented a four-part laboratory sequence for Medical Robotics at the University of Michigan. By integrating manual surgical skills training, commercial robotic system exposure, and custom teleoperation control implementation, the curriculum provides a holistic view bridging theory and practice. Students progress from experiencing surgery as users to designing systems as engineers, developing embodied intuition necessary for informed design decisions.

Assessment results demonstrate substantial improvements in self-efficacy across learning objectives, with particularly strong gains in implementation skills such as virtual fixture programming (+1.91) and haptic force function coding (+1.49). Reflective reports reveal development of nuanced professional judgment, while open-ended challenges generated creative solutions demonstrating learning transfer.

To support adoption by other institutions, the hardware designs and software implementations for Labs 3 and 4 are available as open-source resources:

- Lab 3 (Teleoperation): https://github.com/andyqin18/medrob-lab3
- Lab 4 (Haptics): https://github.com/andyqin18/medrob-lab4

Future work focuses on hardening hardware designs for improved reliability, expanding assessment to include objective performance measures such as task completion times and error rates, conducting comparative studies with control groups, and tracking long-term outcomes as students progress into professional practice or research careers in medical robotics.

Appendix: Lab Survey Questions

Lab 3 – Robotic Medical Teleoperation

Q1: Given a PID control system to tune, I have a strategy for the order in which I tune the parameters.

Q2: After observing a PID control system that is poorly tuned, I understand which parameters to adjust and in which directions.

Q3: I can implement an algorithm to prevent operator tremor from affecting a control system's output.

Q4: I can explain the effects of deadband and backlash on a control system.

Q5: I can explain the effect of control and feedback latency for teleoperation.

Q6: Given a teleoperation system, I can implement an algorithm to provide haptic feedback when the follower encounters resistance.

Q7: Given a teleoperation system, I can implement an algorithm to mitigate the effects of latency for the operator.

Q8: Given a teleoperation system, I could develop experiments to determine its stability, deadband, backlash, and latency.

Lab 4 – Virtual Fixtures and Haptics

Q1: I can describe the most common types of haptic feedback.

Q2: I can implement a virtual fixture using haptic feedback.

Q3: Given a design or specification for a type of haptic feedback, I can write the mathematical expression for force as a function of position and velocity.

Q4: Given a design or specification for a type of haptic feedback, I can write the computer code for force as a function of position and velocity.

Q5: Given a task to complete with a medical robot system, I could recommend appropriate types of haptic feedback to improve operator experience or performance.

Q6: I can explain the limits of haptic feedback regarding strength and stability.

Q7: Given a reference implementation of haptic feedback, I could tune its parameters to improve its effectiveness.

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