VR-406: Haptic Synchronization for Robotic Teleoperation

CDE4301 Interim Report

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Submitted by

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1. Introduction

1.1 The Rise of Robotic Surgery

Robotic-assisted surgery has become the standard of care for many procedures, fundamentally transforming surgical practice over the past two decades. The global robotic surgery market demonstrates explosive growth: from USD 11.83 billion in 2024, the market is projected to reach USD 54.66 billion by 2034, representing a compound annual growth rate (CAGR) of 16.54% (Towards Healthcare, 2024). This extraordinary market expansion reflects both the clinical validation of minimally invasive approaches and the increasing adoption of robotic platforms across surgical specialties.

In urological surgery specifically, robotic approaches have achieved dominance: 62% of prostatectomies worldwide are now performed robotically, with laparoscopic procedures accounting for 37% and open surgery representing only 1% of cases (Williams et al., 2025).

1.2 Clinical Benefits of Minimally Invasive Surgery

Minimally invasive surgery offers substantial and well-documented clinical advantages over traditional open surgery across multiple important patient outcomes:

- **Surgical Site Infections:** 0.8–1.5% (MIS) vs. 3.4–9.33% (Open) — representing approximately 70% reduction (Nahas et al., 2024; Shi, 2023; Aeschbacher et al., 2021)
- **Blood Loss:** 120–250 mL (MIS) vs. 400–719 mL (Open) — approximately 60% reduction (Nahas et al., 2024)
- **Hospital Stay:** 2.1–6.7 days (MIS) vs. 4.4–13.2 days (Open) — approximately halved length of hospitalization (Nahas et al., 2024)

These substantial risk reductions drive increasing demand for minimally invasive procedures. Beyond reducing morbidity, minimally invasive approaches also offer significant cosmetic and functional benefits such as reduction of postoperative pain, faster recovery, and improved patient satisfaction (Gurung et al., 2022; Delongchamps et al., 2013).

1.3 The Emerging Training Crisis

With market growth at 16.54% CAGR and robotic approaches now accounting for 62% of urological procedures globally, there is an urgent need for a proportional increase in trained robotic surgeons (Williams et al., 2025). However, surgical training infrastructure has not kept pace with this demand. Current training methods are inadequate: they are either expensive and inaccessible, lacking realism, and require dedicated training facilities (Roswell Park, 2025). This creates a critical pre-training gap between fellowship completion and independent practice.

Figure 1: daVinci current training methods

2. Problem Clarification

2.1 Tan Tock Seng Hospital Context

To understand the real-world challenges in robotic surgical training, we conducted a site visit and interviews with Dr. Liu Zhenbang, Consultant in the Department of Urology at Tan Tock Seng Hospital (TTSH) in Singapore. TTSH operates robotic-assisted surgical programs, specifically daVinci Surgical Systems, for urological procedures including partial nephrectomy, radical nephrectomy, and radical prostatectomy.

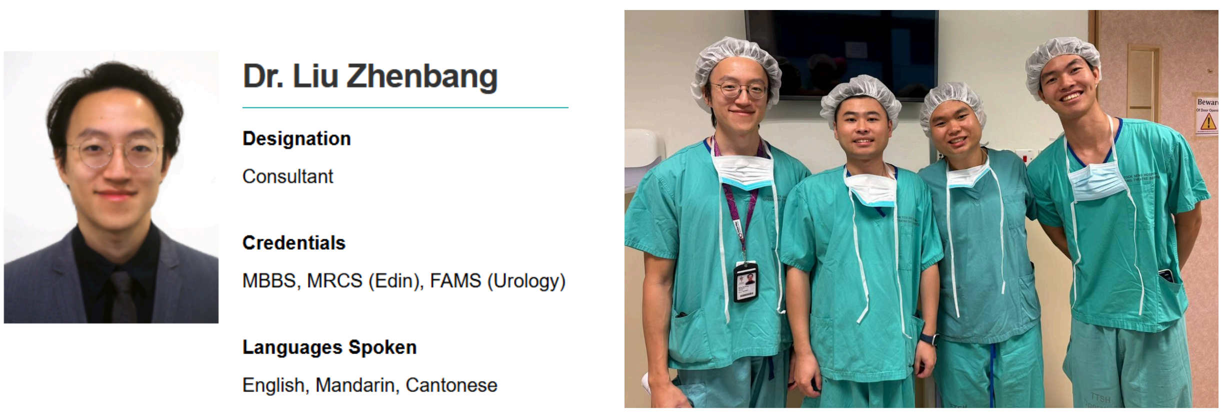

Figure 2: Dr Liu Zhenbang's profile and our visit group photo

2.2 Observed Complexities in Robotic Surgery

During observation of a robotic-assisted partial nephrectomy procedure, we witnessed the remarkable complexity of da Vinci manipulation. This procedure requires:

1. Extreme time constraints:
   Complete nephron-sparing removal (including clamping of the renal artery, precise tumor excision, and renorrhaphy) must be accomplished in approximately 20 minutes before warm ischemia compromises kidney function
2. Complex bimanual coordination:
   Simultaneous control of multiple instruments of 3 robotic arms and 1 camera arm
3. Precision and delicacy:
   Unnecessary force application risks organ damage, bleeding, or suture breakage; excessive hesitation prolongs ischemia time

Observation also revealed the complex surgical team dynamics: beyond the primary surgeon, the operating theater includes a surgical first assistant, surgical technologist, circulating nurse, anesthesiologist, and often a resident learning the system. The resident in particular faces the challenge of transitioning from observer to active participant.

Figure 3: Operation room observation

Figure XX: TTSH doctor operating daVInci simulator

2.3 Current Training Methods and Their Limitations

Generally, three formal training modalities exist (Diaz et al., 2020) (Sridhar et al., 2017):

Training Type	Definition	Advantages	Limitations
Dry Lab Training	Practice on inanimate models using instruments and console	Low cost; Widely accessible; Safe environment	Totally unrealistic compared to living tissue; No cognitive training; Limited value after basics mastered; Cannot replicate bleeding, tissue response, or anatomical variations
Wet Lab Training	Practice using biological tissue (human cadavers or animal models)	Most realistic tissue properties; Enables bleeding scenarios; Improves early learning curve	High cost per case; Limited accessibility; Ethical concerns; Requires specialized facilities; No active expert guidance
VR Simulation (da Vinci Skills Simulator)	Computer-based virtual reality training	Autonomous use; automated objective feedback; standardized curriculum; scalable; no consumables	Very high initial cost (hundreds of thousands of dollars); Lower fidelity than real surgery; Limited cognitive training

2.4 The Pre-Training Gap at TTSH

However, TTSH lacks all three formal training methods due to space and budget limitations! The dedicated da Vinci robots cannot be used for training purposes as they are reserved for clinical surgery. Therefore, the current reality for novice surgeons at TTSH is:

Training Phase	Description
Observation phase	Junior consultants observe surgeries and assist as first surgical assistant
Fellowship (if accessible)	Surgeons obtain external fellowship training, including dry lab and da Vinci simulation (typically 1 year)
Proctorship phase	Surgeons return to TTSH and perform surgeries under expert supervision; minimum **30 proctored cases** required

Independent practice	Surgeon practices independently after successful completion of the proctorship

However, even for fortunate surgeons like Dr. Liu who completed external fellowship training, he reports that the training was "unrealistic and insufficient." Upon returning to TTSH, the opportunity constraints are severe: proctorship sessions occur only approximately once weekly or less frequently, depending on patient case availability and surgeon scheduling.

2.5 The Motor-Cognitive Skills Gap

The transition from observation to proctorship represents an enormous responsibility jump. Dr. Liu describes the gap clearly:

Level	Cognitive Characteristics	Motor Characteristics
Novice doctors	Delayed in locating surgical landmarks (e.g., identifying the renal artery)	Slow, small, jittery movements with frequent hesitation and correction cycles
Expert surgeons	Immediate identification of anatomical landmarks	Swift, precise movements executed confidently and efficiently

Research confirms the critical importance of both motor and cognitive skills:

1. Motor skills: Surgeon technical skill explains 25.8–27.5% of variation in patient complication rates (Stulberg et al., 2020)

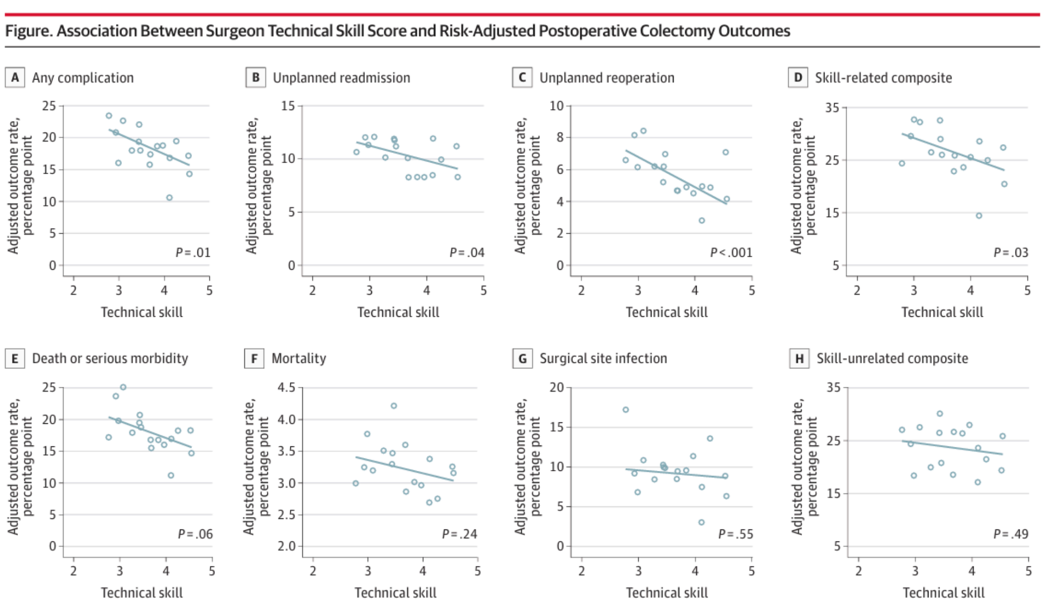

Figure 4: Inverse relationship between surgeon technical skills with patient outcome

2. Cognitive skills: Higher nontechnical skills scores (NOTSS) independently predict decreased complications by 5.1% and decreased mortality by 1.1% (Abahuje et al., 2024)

TABLE 5. Robust Regression Nonadjusted and Adjusted

	Unadjusted		Adjusted	
	*Coef (95%CI)	p-value	Coef (95%CI)	p-value
Any complication	−1.7 (−5.2; 1.7)	0.29	−5.1 (−8.1; −2.0)	0.003
Mortality	−0.8 (−1.6; −0.01)	0.04	−1.1 (−1.8; −0.2)	0.01
Readmission	0.4 (−0.4; 1.3)	0.35	0.4 (−0.5; 1.4)	0.33
Death or serious morbidity	−1.2 (−3.0; 0.5)	0.14	−1.3 (−2.8; 0.1)	0.06
Return to the operating room	−1.0 (−1.8; −0.2)	0.01	−1.1 (−1.9-0.4)	0.005
Surgical site infection	−0.2 (−0.9; 0.4)	0.45	0.1 (−0.5; 0.7)	0.73
Skills-related composite	−4.6 (−7.4; −1.8)	0.002	−5.3 (−8.3; −2.4)	0.001
Skills-unrelated composite	−5.3 (−7.6; −3.1)	< 0.001	−5.6 (−7.9; −3.3)	< 0.001

Figure 5: Correlation coefficient of non-technical skills with patient outcome

2.6 Problem Statement

Despite the exponential growth in robotic surgery demand (16.54% CAGR) and the critical clinical benefits of minimally invasive approaches, a substantial gap exists in surgical training infrastructure. Some of the gaps are

1. Absent motor skill training: TTSH does not have any training module that allows for motor skills training.
2. Inadequate cognitive skill training: Current training methods in TTSH allows surgeon-in-training to participate and observe the surgery, but without proper practice and assessment, it is likely to be inadequate
3. Existing opportunity barriers: The only practice TTSH doctors receive are from fellowship programs, which depend on the Ministry of Health (MOH)'s sponsorship. As such, not every doctor would get to train on robotic surgical systems skills.
4. Existing pre-training gap: Between fellowship/simulator training and proctorship, novice surgeons lack the integrated motor-cognitive expertise needed for safe, efficient practice
5. Prolonged learning curves: Trainees require 30+ proctored patient cases before achieving independent practice, extending training timelines and limiting patient access to care

3. Solution Exploration

3.1 Specific Skills Assessment

3.1.1 Motor Skills Assessment Framework

Global operative performance questions
Respect for tissue
Time and motion
Instrument handling
Flow of operation
Exposure
Tissue planes
Completeness of dissection
Overall technical skill

Figure XX: Global Operative Performance Metric (Stulberg et al., 2020)

This framework, employed by Stulberg et al. (2020), and the JIGSAWS dataset (2014) study linking technical skills to patient outcomes, focuses on observable motor behaviors including:

For our scope, we specifically focus on:

1. Motion:
    a. Path efficiency
    b. Movement smoothness
    c. Economy of movement
2. Time:
    a. Task completion duration
    b. Decision latency
    c. Idle periods

These metrics are directly measurable through haptic interface sensors and provide objective, quantitative assessment of motor proficiency development.

3.1.2 Cognitive Skills Assessment Framework

Hospital .... Trainer name .... Date ....

Trainee name .... Operation ....

Category	Category rating*	Element	Element rating*	Feedback on performance and debriefing notes
Situation Awareness		Gathering information		
		Understanding information		
		Projecting and anticipating future state		
Decision Making		Considering options		
		Selecting and communicating option		
		Implementing and reviewing decisions		
Communication and Teamwork		Exchanging information		
		Establishing a shared understanding		
		Co-ordinating team activities		
Leadership		Setting and maintaining standards		
		Supporting others		
		Coping with pressure		

* 1 Poor; 2 Marginal; 3 Acceptable; 4 Good; N/A Not Applicable

1 Poor	Performance endangered or potentially endangered patient safety, serious remediation is required
2 Marginal	Performance indicated cause for concern, considerable improvement is needed
3 Acceptable	Performance was of a satisfactory standard but could be improved
4 Good	Performance was of a consistently high standard, enhancing patient safety; it could be used as a positive example for others
N/A	Not Applicable

Figure XX: Nontechnical Skills for Surgeons (NOTSS) (Abahuje et al., 2024)

The NOTSS framework, validated in the prospective study demonstrating direct links between cognitive skills and patient mortality, encompasses multiple cognitive domains. For our training system, we focus on three critical components:

1. Gathering Information
    a. Visual scanning patterns to identify anatomical landmarks
    b. Recognition of tissue characteristics and pathology
    c. Assessment of instrument positioning

2. Understanding Information
    a. Interpretation of visual cues
    b. Situational awareness
    c. Recognition of normal vs. abnormal states

3. Projecting/Anticipating Future States
    a. Predicting tissue behavior under manipulation
    b. Planning next movements based on current surgical field state
    c. Forward-thinking to maintain procedural flow and efficiency

3.1.3 Skills Validation

Dr. Liu's clinical example illustrates the need for these skills: when the renal artery is located posterior to the kidney:

Level	Cognitive Characteristics	Motor Characteristics
Expert surgeon	**Immediately** identifies the artery location based on anatomical knowledge and visual cues	Executes **one swift, precise** movement to grasp the artery without injury
Novice surgeon	**Delayed** in locating the artery; uncertain about depth and position	Performs **many slow, small, jittery** movements with multiple correction attempts

This real-world scenario demonstrates that cognitive knowledge (knowing where the artery is) must be coupled with motor skill (executing the precise grasp) to achieve expert performance. Training one without the other leaves a critical competency gap.

Figure XX: Dr Liu validating the need for motor and cognitive skills in renal artery extraction

3.2 Literature Review

3.2.1 Haptic Feedback

3.2.1.1 Evidence for Haptic Feedback Effectiveness

Having identified motor skills as a critical training target, particularly proprioception movement, we systematically reviewed evidence on haptic feedback effectiveness in surgical training.

1. Meta-Analysis Evidence (Bergholz et al., 2023)

A comprehensive meta-analysis examining 51 studies found that 67% of studies (34/51) demonstrated statistically significant performance improvements with haptic feedback across three key metrics: task completion time, accuracy of movement, applied force control

2. Force Reduction Benefits (Azher et al., 2024)

A systematic review specifically examining force-related outcomes revealed dramatic benefits:

- 83% reduction in average applied forces with haptic feedback
- 69% reduction in peak forces with haptic feedback

This force reduction is critically important in robotic surgery where excessive force risks suture thread breakage, may cause organ damage or bleeding, and visual force estimation alone is insufficient for novices

3. Dr. Liu's Clinical Validation

When asked specifically about haptic feedback for training, Dr. Liu affirmed: "Especially motor skills can be taught more effectively through using haptic feedback. Although there are variations of manipulation among surgeons, it would be beneficial for the novice surgeons to learn from the experts instead of figuring the movement on their own."

This clinical endorsement from an experienced robotic urologist validates the relevance of haptic training for real-world surgical practice.

3.2.1.2 Dual-User Haptic Feedback Study (Zhang et al., 2023)

Study Design and Methodology:
Zhang et al. (2023) developed a novel dual-user haptic training system specifically for laparoscopic surgical training. The study investigated whether haptic feedback would have differential impacts based on task characteristics—specifically hypothesizing that “haptic feedback would facilitate orientation tasks more than cutting tasks”.

“On-Demand” haptic feedback mode, in which expert intervened when trainee made errors or struggled, providing corrective forces without verbal communication

Results:

Metric / Task	Finding
Overall time	No statistically significant difference
Grasping time (orientation task)	Haptic group showed significantly reduced grasping time compared to control group
Cutting time (executive task)	No statistically significant difference

Key Finding:
"Haptic feedback has a more substantial impact on orientation tasks than on cutting tasks in laparoscopic surgery training."

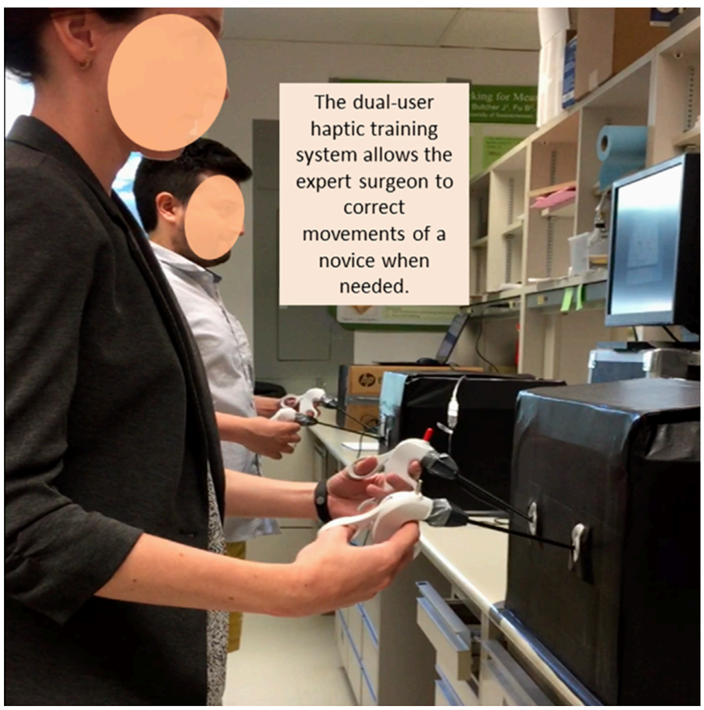

Figure XX: Laparoscopy haptic experiment setup

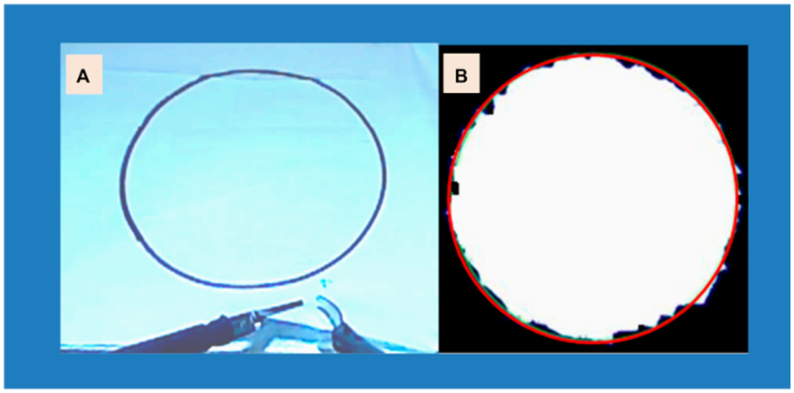

Figure XX: Laparoscopy haptic experiment task

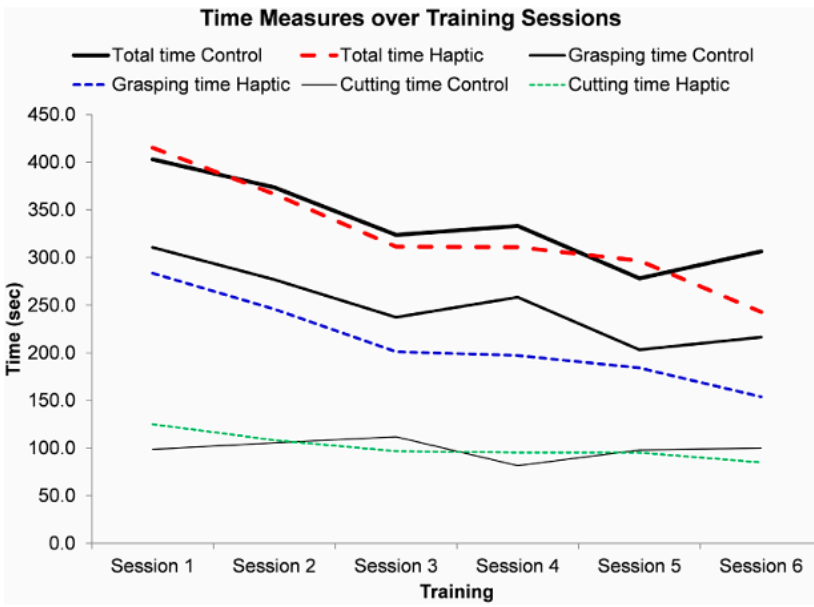

Figure XX: Laparoscopy haptic experiment result

3.2.1.3 Interpretation and Limitations

Haptic feedback benefits orientation tasks more because:

- Fast, feedforward tasks (cutting) rely on pre-planned motor commands, while
- Slow, feedback-dependent tasks (grasping, positioning) continuously incorporate sensory information to adjust trajectory in real-time

Therefore, haptic guidance can directly influence feedback-controlled movements (orientation, positioning, grasping), effectively "teaching" optimal motor patterns through physical guidance.

Study Limitations:
1. Simple Task: The circle-cutting task was simple and does not represent actual surgical procedures. Similar learning rates between groups may be due to task simplicity; more complex tasks might show greater haptic benefits
2. Lack of Cognitive Training: Focus solely on motor skill transfer. Does not address cognitive decision-making component identified as critical

3.2.2 Collaborative Training

3.2.2.1 Experimental motivation and setup

Ganesh et al. (2014): "Two is Better Than One" investigated the fundamental motor responses and adaptations that govern physical interactions between humans. They developed a novel interactive learning paradigm that differs critically from previous joint action studies. Pairs of individuals were physically connected during a motor task without conscious knowledge of the connection. This eliminated cognitive complications from conscious coordination, which enable investigation of pure reactive motor adaptations driven solely by haptic signals

Critical Design Feature:
The compliant connection allowed independent movement while transmitting partner forces. Subjects had to actively track the target, they could not simply relax and follow their partner. Subjects were not informed about the nature of forces and were not consciously aware of the connection with their partner (verified by post-experiment questionnaire).

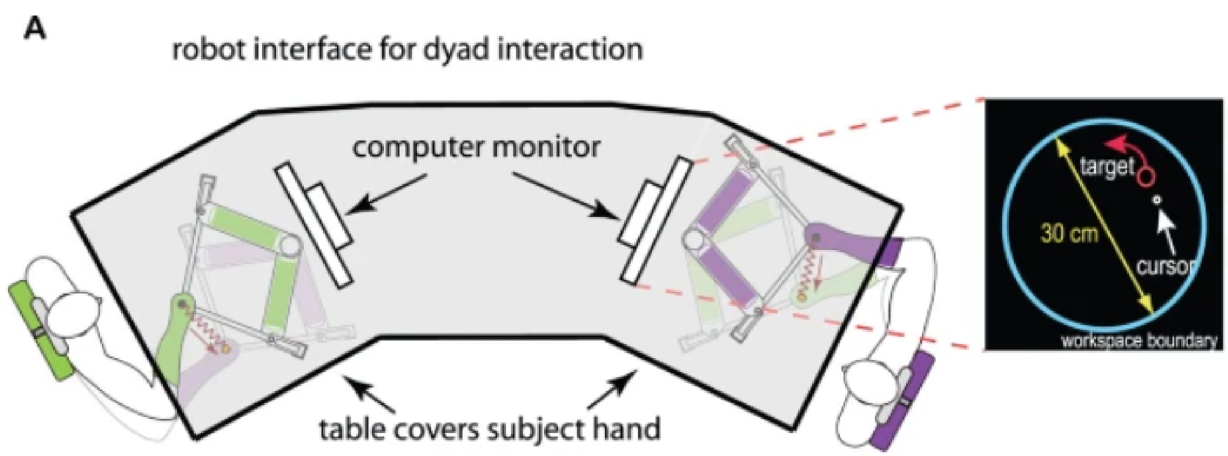

Figure XX: Collaborative haptic experiment setup and task

3.2.2.2 Key Findings: Mutual Benefits Regardless of Relative Performance

Finding 1: Connection with a Partner Improves Performance

The central discovery: "Connection with a partner improved the task performance in an individual irrespective of whether the partner's performance was better or worse than the individual's own performance." (Ganesh et al., 2014)

- When connected to a better-performing partner (positive x-axis): Individual performance improved
- When connected to a worse-performing partner (negative x-axis): Individual performance still improved

This counterintuitive finding demonstrates that physical interaction is fundamentally beneficial, not merely a transfer from expert to novice.

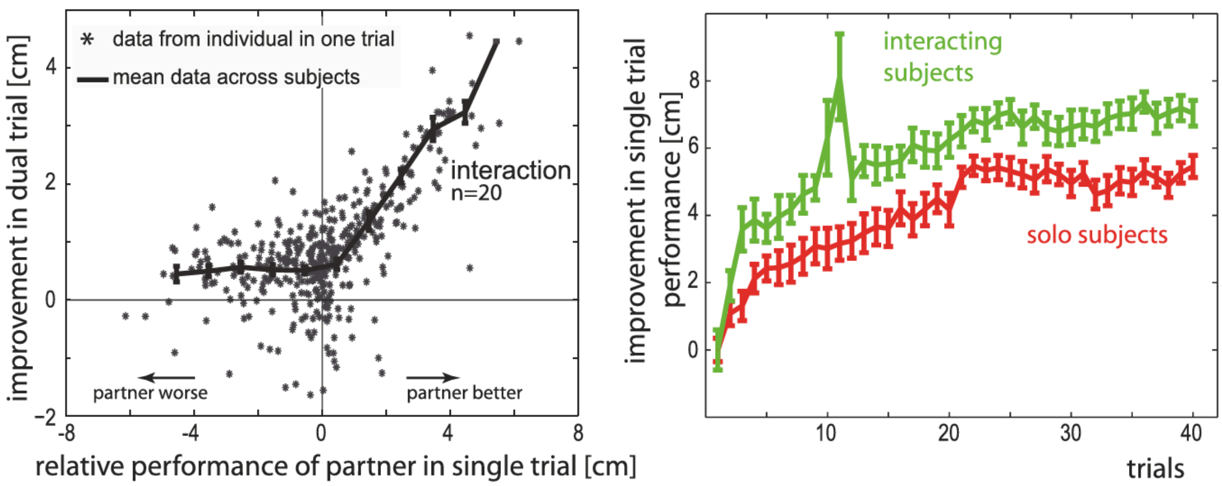

Figure XX: Improvement of performance through collaborative training

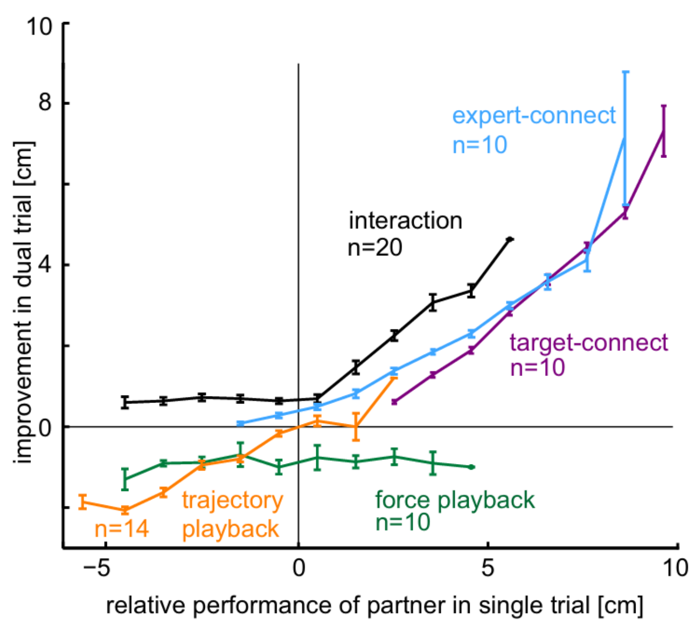

Figure XX: Improvement based on modes of interaction

3.2.2.3 Critical Insights

- Physical connection is inherently beneficial regardless of skill difference. Reactive motors adapts driven by haptic feedback.
- Mutual adaptation outperforms passive or pre-recorded guidance. Non-reactive systems cannot reproduce these learning effects, even when the expert partner makes small errors
- The physical connection enables novices to feel expert adjustments and experts to feel novice deviations, creating a feedback loop that produces lasting motor learning, not temporary assistance.

3.3.3 Differentiating Features

Feature	Zhang et al. (2023)	Ganesh et al. (2014)	Our System
Physical Connection	Yes	Yes	Yes
Surgical Context	Yes	No	**Yes (robotic surgery)**
Haptic Feedback Type	On-demand correction	Continuous elastic link	Variable-stiffness collaborative
Cognitive Training	None	None	**Integrated (NOTSS-based)**
Task Complexity	Simple (circle cutting)	Simple (tracking)	**Meaningful surgical subtasks**
Two-Way Interaction	Limited	Full mutual adaptation	Full mutual adaptation

3.3 Value Proposition

FOR: Robotic surgery novice doctors
WHO: Require pre-training before proctorship
OUR: Collaborative Haptic Teaching System
IS: A guided practice platform
THAT: Enables expert surgeons to actively guide novice hand movements to transfer cognitive and motor skills, bridging observation with real surgery

4. Concept Design

Design specifications

that you are required to meet (Scoping: degree of freedom, etc)

Design details: How are you trying to achieve these?

5. Detail Design

6. Prototyping

6.1 XXX Prototyping

7. System Evaluation

7.1 Experiment Design

7.2 Data Collection

7.3 Result Analysis

8. Limitations and Future Work

References

Appendices