Patterns of Identifying Errors in Laparoscopic Simulation Training: Constructing the PIE Framework

Sheng-en, Peng

Department of Cognition, Data and Education

MSc Psychology, University of Twente

First supervisor: Dr. Marleen Groenier (TG)

Second supervisor: Dr. Russell.W. Chan (CODE)

Date: August 30th, 2024

APA 7th edition

Abstract

Background: Errors in minimally invasive surgery (MIS), particularly in laparoscopy, are a critical concern despite ongoing technological advancements and improved safety protocols. Early phase is crucial, as trainee surgeons are more likely to perform errors due to lack of experience and skill. Effective error identification and recovery strategies are essential to improving performance and patient safety. Simulation training has been shown to enhance error detection and recovery, but a deeper understanding of the specific patterns cognitive and motor processes involved is needed to optimise training and outcomes.

Method: This thesis employed a two-study approach to address these concerns. Study 1 used Problem-Centred Expert Interviews (PCEIs) with three Subject Matter Experts (SMEs) in laparoscopy to develop the Patterns of Identifying Errors (PIE) Framework. This interview aimed to identify a common error and construct a framework explaining the cognitive processes in early laparoscopic training, focusing on error detection, evaluation, and recovery. Study 2 utilised electromyography (EMG) with two participants to investigate the relationship between muscle co-activation and tissue damage in simulated laparoscopic tasks, providing insights into motor learning and control.

Results: Study 1 suggested 4 cognitive process patterns namely, error detection, labelling, evaluation and recovery, highlighting spatial disorientation and excessive force as prevalent errors among intermediate surgeons. Study 2 demonstrated that muscle co-activation of the right muscle increases over time. Tissue damage reduction were only found in participant two

Discussion: Study 1successfully developed the PIE Framework, highlighting spatial disorientation and excessive force as prevalent errors among intermediate surgeons. The study underscored the importance of precise instrument handling and supervisory feedback in managing these errors. Study 2 demonstrated that muscle co-activation patterns, can reflect learning effect on muscle with more consistent motor control improvements. While EMG proved effective in measuring muscle activity, the study could not definitively establish a causal link between muscle co-activation and tissue damage due to limitations in data analysis.

Conclusion: This thesis is a pioneering effort to map cognitive processes involved in error identification and investigate muscle co-activation in simulated laparoscopy. Despite limitations, it offers valuable insights into error patterns and motor control, providing a foundation for future research aimed at enhancing laparoscopic training and performance.

Keywords: Simulated-based laparoscopy training, cognitive process, motor process, muscle co-activation

Acknowledgement

Words cannot express my gratitude to my thesis supervisor Dr Marleen Groenier, for being my motivator and mentor throughout the thesis project. Her invaluable patience and feedback have significantly shaped the development of this thesis. Her guidance and insightful critiques have been instrumental in refining the research and achieving the final outcome. Her dynamism, vision and sincerity have deeply inspired me and added colours to my interest in the field of Human Factors and Engineering Psychology. I would like to express my sincere gratitude to my second supervisor, Dr. Russell W. Chan, for his valuable feedback during the revision of my thesis and his expert guidance on the analysis of EMG data. His critical insights and constructive comments have greatly contributed to improving the quality of my work. I would not have been able to complete this thesis with full confidence without the support from my supervisors. It was a great privilege and honour to work and study under their guidance.

I would also like to express my heartfelt appreciation to my interviewees, whose valuable insights and contributions greatly enriched this research. Your willingness to share your experiences and perspectives was instrumental in the success of this study. Additionally, I extend my gratitude to the participants, whose involvement was crucial in shaping the outcomes of this research. Your engagement and support played a significant role in the successful completion of this study. This thesis benefited from the use of ChatGPT, an AI language model by OpenAI, which assisted in refining and enhancing the clarity of the content.

Furthermore, no words cannot express my gratitude to my Enschede guardian angels Karl Hinrichs and Bianca Hinrichs. You have been a constant source of love, guidance, and protection, standing by my side with unwavering support and care. Your selfless acts of kindness have provided me with a sense of security and stability that is beyond measure.

Your presence in my life has been a beacon of light, illuminating my path and ensuring that I never feel alone. Of course, I will not forget the lovely 3 dogs of theirs Saar, Juul and Noor, who have provided me with unconditional love and been my best study buddy.

Lastly, with heartfelt gratitude and immense appreciation, I would like to acknowledge my parents and my sister. Their unwavering support and belief in me throughout my academic journey in the Netherlands have been a cornerstone of my success. My parents' unconditional love, encouragement, and steadfast support have profoundly shaped who I am today. Similarly, my sister's support and understanding have been a source of strength and motivation. Dear Mama and Papa, your roles in my life are cherished beyond measure, and your support has been invaluable.

Table of Contents

Introduction

In the past two decades, it has become increasingly apparent that human errors in minimally invasive surgery (MIS) are neither rare nor uncorrectable. The landmark report "To Err is Human" by the Institute of Medicine (IOM) published in 2000 (Kohn et al., 2000), introduced the term human error and its role in patient safety (Kopec et al., 2003). The report has triggered research on identifying different types of human errors in healthcare settings and recovery strategies.

Laparoscopy, as the most performed MIS procedure, plays a critical role in extirpative and reconstructive techniques across various surgical disciplines (Gallagher & Satava, 2002) The existing literature offers multiple definitions of laparoscopy. However, in general terms, according to Soper et al. (1994), laparoscopy refers to a medical procedure involving video-assisted technology to visualise the abdominal cavity using an endoscope or telescope, subsequently followed by a diagnostic of therapeutic methods. This approach offers substantial benefits, including reduced recovery times (Mandrioli et al., 2016), enhanced cost-effectiveness (Di Saverio, 2014), and minimised incision size (Nezhat, 2008).

Despite the advantages of laparoscopic surgery in enhancing patient outcomes and the advancements in technology and safety protocols, can it be anticipated that laparoscopic procedures will be entirely devoid of errors? Certainly not, although efforts can be made to minimise errors in laparoscopy, they may still occur. However, their frequency should be low and not detract from the overall benefit of the procedures (Drăghici et al., 2017). Errors can be mitigated through simulation training during the early learning phase. The study of Ahlberg et al. (2007) suggested that simulation training not only improves intraoperative performance among inexperienced residents but also that they are likely to perform with fewer errors when compared with the group without simulation training. Similarly, a study by

Sandy et al. (2013) demonstrated that through virtual reality surgical simulation laparoscopy training, novice surgeons showed a significant reduction in error rates and better performances. Along with improving performances, surgeons are also likely to develop the ability to identify errors and come up with recovery strategies. According to Satava (2005), effective error identification and recovery in surgical practice start by recognising error that leads to consequences. This study further explained the relationship between error identification and recovery, by highlighting the immediate detection of errors greatly enhances the probability of correcting errors with minimal impact on patient outcomes. In contrast, errors recognised at the last stage of execution of an action are more likely to lead to more severe consequences for the patient. Moreover, Satava (2005), argued that simulators can “teach” surgeons how to identify errors and develop recovery strategies effectively. Moreover, multiple studies also determined that psychomotor and visual-spatial skills are crucial skills for identifying errors and developing effective recovery strategies (Henn et al., 2018; Prasad et al., 2016). Therefore, there are errors in laparoscopy surgery, but their occurrence remains attributed to human factors. However, surgeons can identify errors and develop recovery strategies through simulation training and advanced psychomotor skills as well as visual-spatial skills during the early learning phase.

This exploratory thesis aims to determine patterns of behaviours that contributed to errors in unsupervised training on surgical simulators. By identifying specific patterns in cognitive and motor processes, such as muscle co-activation, this thesis seeks to provide valuable insights that surgical experts, researchers and trainees can use to better understand behaviours prior to error and develop effective strategies for intervention and improvement in simulated-based training. Given the current staff shortages in healthcare, there is an increasing need for flexible and adaptive training systems. With supervised training becoming more limited, technological advancements in performance monitoring and assessment enable trainees to practise independently using simulators, addressing the challenge of reduced direct supervision. This thesis supports the development of adaptive training systems that can address these constraints, ultimately enhancing the effectiveness and outcomes of surgical training programs.

1.1 Errors in Laparoscopy

Based on the existing works of literature, there appears to be no exact definition for error in laparoscopy. Although laparoscopy errors cannot be precisely defined, the available literature provides a rich definition of medical errors. For instance, Reason (1990) stated that an error in medical care occurs when a planned action is not completed as intended (an error of execution) or when an incorrect plan is used (an error of planning). On the other hand, Leape (1994) defines medical error as an unintended act or omission that does not achieve the intended result. However, Grober and Bohnen (2005) argued that Reason's (1990) and Leape's (1994) definitions hold a limitation, suggesting that unintended outcomes should be blamed for medical error. Instead, medical errors are an act of omission or commission within the planning or execution phases, which contributes to an unintended outcome (Grober and Bohnen, 2005). This definition can also be applicable in other settings, including laparoscopic surgery, not just because laparoscopy is situated within the domain of the medical field, but also because the performance of laparoscopy requires careful planning and execution (Gerges et al., 2006). Therefore, this thesis views errors in laparoscopy as acts of either omission or commission within the planning or execution phases of laparoscopic procedures, resulting in unintended outcomes, aligning with the study of Grober and Bohnen (2005).

1.2 Literature Review on Errors in Laparoscopy

A literature review was conducted to investigate errors in laparoscopy, focusing on both empirical and theoretical aspects. This review specifically examined cognitive and motor processes, as well as execution errors within the field. The search terms used included "common error," "behavio(u)ral error(s)," "motor error(s)," and "cognitive error(s)," combined with terms such as "laparoscopy," "laparoscopic surgery," "minimally invasive surgery," "intermediate(s)," and "simulat(ed)or training(s). The search was limited to original research articles published in English-language peer-reviewed journals. Articles that did not align with the review's focus based on their titles were excluded, and abstracts that lacked relevant descriptions of motor, cognitive, procedural, or execution errors were also omitted. The review included only studies that addressed these types of errors in laparoscopic surgery. Literature searches were performed using Scopus and Web of Science databases. The initial search yielded over 6,000. Following a thorough screening process, which involved evaluating the relevance of titles and abstracts against predefined inclusion and exclusion criteria, over 5500 of papers were excluded. The results of the literature review are reported in section 1.4 Common Error in Laparoscopy.

1.3 Types of Errors in Laparoscopy

Previous studies have identified different types of errors. Joice et al. (1998) conducted a pivotal study using industrial Human Reliability Assessment (HRA) to evaluate video-recorded laparoscopic cholecystectomies, revealing that errors in laparoscopy can be categorised into two types: procedural errors and execution errors. An execution error occurs when the speed, force, distance, or timing is incorrectly applied as a result of either omitting or mis-organising steps, and a procedural error occurs when a step is omitted or re-ordered incorrectly (Joice et al., 1998). These findings highlight that errors in laparoscopy can often be traced back to specific aspects of surgical procedures, providing a framework for understanding and addressing the challenges inherent in laparoscopic techniques. In other words, surgeons can often use this approach to review their performance by examining where and why errors occurred in their procedures. This thesis will focus on execution errors, given their high likelihood of occurrences in laparoscopic procedures based on Joice et al (1998)'s study. Thus, addressing execution errors will provide a solid foundation for constructing the patterns of error identification framework.

1.4 Common Error in Laparoscopy

To further construct the framework, it is essential to first identify the most common error encountered in laparoscopy. By doing so, this approach provides a pathway for developing the framework and will be used to design the experiment subsequently.

To gain a deeper understanding of common errors occurring during execution, the research employed the aforementioned methodology with a specific focus on the keyword "common error" to identify and analyse these frequent issues. The result of the literature search is presented in Table 1. As demonstrated, all three identified sources highlighted excessive force as a significant issue, while opinions on other error types differ. Therefore, it is essential to further investigate the role of excessive force in this context.

Table 1

Literature Research Result on Common Errors in Laparoscopy

Article no.	Authors	Types of common error
1	Tang et al. (2005)	● Omission of important steps ● Execution of steps in the wrong sequence ● Use of excessive force

2	Bonrath et al. (2015)	● Inadequate use of force/distance ● Inadequate visualisation during grasping/dissecting ● Incomplete suturing
3	Tang et al. (2004)	● Excessive force ● Excessive movement in the wrong direction ● Misorientation in tissue planes

Excessive force occurs when surgeons have a misperception of the force that they are applying to the probes and forceps, leading to application of excessive force. The study of Tang et al, (2005) indicated that excessive force is a major contributing factor to errors among trainees, accounting for 92% of consequential mistakes in laparoscopy. As a consequence of this inadequate use of excessive force, tissue damage frequently occurs (Wottawa et al., 2012; Cundy et al., 2015; Bonrath et al, 2015). Excessive force is also classified as an execution error, as it involves the incorrect application of force. This classification aligns with the study of Joice et al. (1998) discussed earlier. Therefore, recognising excessive force as a common error will act as a strong pathway to further construct the patterns of error identification framework.

1.5 Factors Affecting Error Performance in Laparoscopy

To master minimally invasive surgery requires surgeons to have high visual-spatial abilities and psychomotor abilities (Gallagher et al., 2003; Luursema et al., 2012). Studies examining laparoscopy performance in a simulated environment have demonstrated the crucial role of visuospatial abilities. The simulator training study by Luursema et al. (2012) highlights the importance of visuospatial skills, particularly the ability to manipulate complex visual stimuli, which are crucial in laparoscopic procedures where surgeons rely on indirect visual cues to navigate and operate in confined spaces. These skills play a vital role in the development of surgical proficiency, with their impact being most pronounced during the early and late stages of skill acquisition. This indicated that high visualisation skills are linked with reduced tissue damage and increased motion efficiency. Similarly, the Abe et al. (2018) study shows that visual-spatial ability influences the learning of robotic suturing skills. Surgeons with higher visual-spatial skills perform better in robotic suturing. In summary, both studies underscore the critical influence of visuospatial ability in minimally invasive surgical techniques. These findings suggest that surgeons with higher visuospatial skills tend to progress more effectively through the stages of skill acquisition, particularly in the early and late phases of training.

Psychomotor ability, another critical component in surgical performance, plays a fundamental role in the precise execution of laparoscopic procedures. According to Groenier et al. (2015), basic laparoscopic skills are acquired through psychomotor skills. Their simulator training study indicates that psychomotor skills predict the time required for training and the rate at which proficiency is achieved. Concluding that enhanced psychomotor ability is associated with faster task completion, reduced tissue damage, and more efficient movements.

Furthermore, the studies established that learning curves and repeated measures analyses are effective tools for mapping surgeons' performance throughout their skill development. This paper will utilise the research of Luursema et al. (2012) and Groenier et al. (2015) as the foundation for the experimental study (See chapter 3). However, it is unclear how psychomotor skills and visual-spatial skills play a role in patterns of error identification among laparoscopy surgeons.

1.6 Error Identification in Laparoscopy

Experience enhances a surgeon's ability to identify and manage errors during laparoscopic procedures, as has been well demonstrated. Humm et al (2023) found that experienced surgeons showed superior skills in interpreting errors, emphasising the significant impact of experience on the ability to manage errors. Such improvement is most likely due to the learning impact that is resulting from engaging in both cognitive and motor processing. However, there is currently a lack of understanding of error identification in simulated laparoscopy training, highlighting the need for future research to look further into how errors are identified and addressed in simulated laparoscopic procedures.

Two studies have provided valuable direction and research methods on how to address this gap in understanding error identification in simulated-based laparoscopy. The study by Craig et al. (2012) demonstrated that interviews with experts can capture cognitive processes related to decision-making in laparoscopy surgery. Experts provide detailed insights into specific mistakes and novice traps encountered during surgery. However, this study focused on identifying the critical decision surgeons need to make during laparoscopy surgery, rather than exploring the cognitive process patterns associated with errors and error recovery in simulated-based laparoscopy. Despite this, the study of Craig et al. (2012) offered a valuable method for further investigation, suggesting that interviews with experts can provide deeper insights into these cognitive processes.

Moreover, the study of Zhu et al. (2011) highlights the usefulness of physiological data, such as Electroencephalography (EEG), in reflecting motor processes during laparoscopic learning. This study demonstrates how EEG data can objectively capture the neural mechanisms underlying various motor learning paradigms. Although this study did not specifically address error identification in simulated laparoscopic tasks, it provides a valuable framework for future research, suggesting the potential of using physiological data to investigate patterns of motor processes associated with errors and error recovery in laparoscopic performance during simulated training.

The limited information available on patterns of error identification in laparoscopy highlights the need for further research. Understanding these patterns is crucial for improving training methods, enhancing surgical outcomes, and minimising patient risk. This thesis aims to bridge this knowledge gap by investigating the underlying cognitive and motor processes related to error identification among trainees in a simulated-based laparoscopy training and proposing a structured framework for better error recognition and recovery strategies.

1.7 Error Recovery Strategies in Laparoscopy

Error recovery strategies are crucial in minimising errors and improving performance, particularly in complex fields such as laparoscopy. Error recovery is a critical safety goal in complex man-machine systems, encompassing strategies such as information search, planning behaviours, and learning from errors (Kontogiannis, 1999). It is also recognised as a vital skill for ensuring safe surgical practice and is an essential educational focus for learners during surgical training (Gabrysz-Forget et al., 2021). Error recovery strategies involve systematic approaches and techniques that are designed to address and correct errors during task execution. Error recovery strategies can significantly reduce the frequency and impact of mistakes by enabling surgeons to identify, assess, and correct them quickly.

1.7.1 Supervisor's Feedback

Evidence from numerous studies underscores the importance of feedback and simulation training in error recovery strategies. Feedback, in particular, is vital, as it offers real-time, specific corrections that help surgeons understand and refine their technique. In the early learning phase of laparoscopy, supervisory feedback is predominantly used to limit error performances and the ability to develop strategies. The study of Strandbygaard et al.

(2013) has proven the important relationship between supervisor feedback and the efficiency of residence training. Their experiment results have suggested that supervisory feedback positively affects residents' motion efficiency during their early training phase. Similarly, Bjerrum et al. (2015) have also found that the novice's efficiency movements in simulation-based training increased by supervisor feedback.

Based on the existing studies, supervisory feedback significantly enhances trainee efficiency. However, it remains uncertain whether supervisory feedback is formally recognised as an effective error recovery strategy in simulated based laparoscopy training. Consequently, this thesis hypothesises that supervisor feedback will be identified as a viable error recovery strategy in the early training phase of laparoscopy training.

1.7 Purpose of Present Thesis

The goal of this thesis is to develop a comprehensive framework for identifying and analysing cognitive and motor processing patterns of error in laparoscopic performance during simulation training to enhance error recognition and improve recovery strategies in laparoscopic procedures, which is named the Patterns of Identifying Errors (PIE) Framework. Through constructing the PIE Framework, the present thesis aims to investigate the following research question:

RQ: "*Which cognitive and motor processes are associated with errors and error recovery during laparoscopic performance in simulated training* "

The current paper is expected to provide valuable insights into error identification and recovery within simulated-based training for laparoscopy by constructing a framework. Moreover, this thesis is expected to reveal patterns of the cognitive and motor processes that occur when engaging with errors during simulated laparoscopy tasks.

Moreover, the research is expected to reveal patterns in cognitive and motor processes that occur when engaging with errors during simulated laparoscopy tasks. This will be achieved through Problem-Centred Expert Interviews, which will provide insights into the cognitive strategies used, and through an experimental study utilising electromyography (EMG) to analyse motor processes. Together, these methods will help uncover how participants manage errors both mentally and physically during simulated laparoscopy training.

1.8 Overview of this thesis

This thesis is a two-part study. The first study (see Chapter 2 involved conducting an interview study to identify common errors and recovery strategies from the perspective of laparoscopic experts. These interviews were used to develop a foundational framework for the PIE (refer to Chapter 2: Interview Study). The follow-up study, (see Chapter 3: Experimental Study) involved examining two error pathways through laparoscopic performance on the LapSim simulator, analysing EMG signals, and evaluating think-aloud data. Based on these data, the foundational framework and proposed recovery strategies can be tested and refined accordingly. Finally, a refined PIE framework will be proposed, offering a clear structure for understanding error identification patterns among laparoscopic surgeons and outlining effective recovery strategies.

2. Interview Study

2.1 Introduction

The previous section (see section 1.4 Common Error) has demonstrated that excessive force has been identified as a common error in laparoscopy. Studies have supported this recognition by demonstrating the positive relationships between excessive force and tissue damage. However, focusing solely on excessive force offers a limited scope to understand the error identification patterns, as it does not encompass the full spectrum of factors contributing to procedural mistakes. To achieve a more comprehensive understanding, it is essential to identify additional common errors. Given that the existing literature does not offer comprehensive insights into additional errors, this thesis employed the task analysis method to identify another potential error and its role within the field.

This thesis employed Problem-Centred Expert Interviews (PCEIs) methodology, conducting semi-structured interviews with Subject Matter Experts (SMEs) in laparoscopy to identify and analyse recurrent errors occurring in laparoscopic procedures. The SMEs, who possess extensive expertise and practical experience in the field, were systematically interviewed to gain in-depth insights into the nature and frequency of these errors. This approach aimed to explain common issues within laparoscopic practices, thereby enhancing the understanding of error dynamics and informing potential improvements in procedural protocols. Interviews with subject matter experts in laparoscopy are beneficial in research as they help identify critical steps, technical skills, and common errors (Ritter et al., 2019). These experts are able to provide insights into patterns and themes in laparoscopic errors based on their extensive experience, which might not be readily apparent to researchers and are often not highlighted in literature studies.

The aim of this interview is to determine the underlying cognitive process patterns related to error and error recovery in laparoscopy for simulated-based training. Moreover, the interview also aims to establish a conceptual framework for the Patterns of Identifying Error (PIE) Framework. This framework is designed to delineate two distinct pathways for error identification: (1) excessive force, and (2) an additional common error identified through the interview process. The current study investigates the following primary research question: "*What insights can subject matter experts provide regarding the common errors committed by intermediate practitioners during the early learning phases of laparoscopic surgery?"* Additionally, this paper addresses the sub-question: "*Based on the experiences of subject matter experts, what cognitive process patterns of error identification and strategies for error recovery are observed among intermediates during the early learning phases of laparoscopic surgery?*" It is anticipated that the findings from this interview will further validate the hypothesis that excessive force contributes to tissue damage, particularly among intermediate practitioners during the early learning phase of laparoscopic surgery.

2.2 Method

2.2.1 Participants

Three expert MIS surgeons were recruited for the interview through the volunteering sampling methods. Invitations were sent via email, providing detailed information about the research aims, and procedures, and obtaining explicit consent for data analysis. All interviewees were MIS experts with an average of 17 years of surgical experience (*SD* = 9.3). For this research, MIS experts were defined as those who have completed at least a surgical residency, with minimum five years of advanced MIS experience in a clinical setting, and hold certification as surgeons in the Netherlands. Furthermore, all participating experts had successfully completed the standard MIS course during their residency and had demonstrable experience training laparoscopic intermediates.

2.2.2 Ethical Approval

The ethical approval for this study was obtained from the Ethics Committee of the Natural Sciences & Engineering Sciences at the University of Twente, with reference number 240299.

2.2.3 Study Design

This study employed an inductive qualitative design (Azungah, 2018) and involved semi-structured, problem-centred interviews with experts. Qualitative content analysis (Mayring, 2000) was performed on the data collected from the interviews.

2.2.4 Apparatus

The interviews were conducted through Microsoft Teams. The interviews were conducted through Microsoft Teams.Microsoft Teams was employed for dual purposes: as an online video conferencing platform and as a tool for recording and transcribing the interviews.

2.2.5 Materials

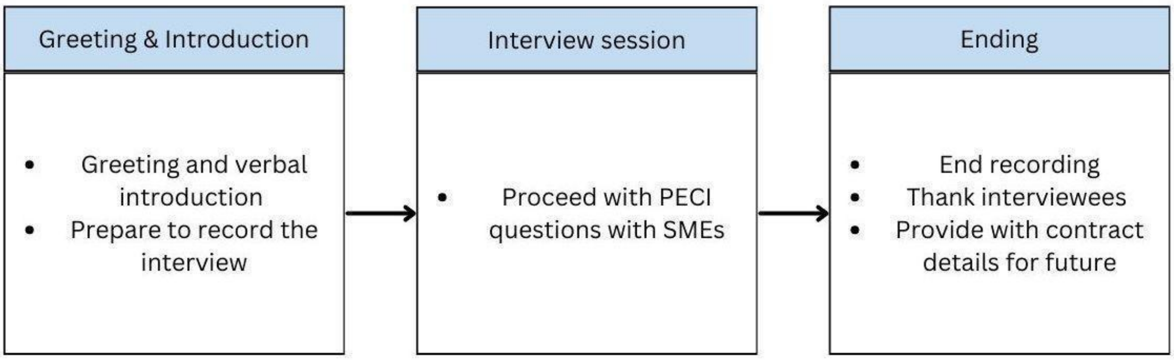
An interview plan was constructed, comprising both structured questions and prompts for the interview (see Appendix A). Additionally, it includes a standardised script for the verbal interview highlighting outlines of the research objectives, interview procedures, and participant's rights. This ensures uniformity in the information provided to all interviewees. Prior to the interview, informed consent was sent to the participant, which they duly signed and returned via email, thereby indicating their voluntary agreement to participate (see appendix A).

2.2.6 Procedure

Informed consent forms were sent to the interviewees via email prior to the interviews. The signed consent forms were then returned by the interviewees. Interviewees were warmly greeted and thanked for their participation. Then, they received a verbal introduction outlining the research aim, procedure, their rights of participation and data handling. If participants have no further questions, the interview commences with recording. Interview questions were asked in the order listed in the interview plan (See appendix A). Finally, the interviewee was again thanked for their time and input and ensured they had no further questions. They were also provided with the contact information of the interviewer, supervisor, and ethical committee for any future inquiries. View Figure 1 for procedure visualisation. The interview lasted about one hour.

Figure 1

Visualisation of Interview Procedure



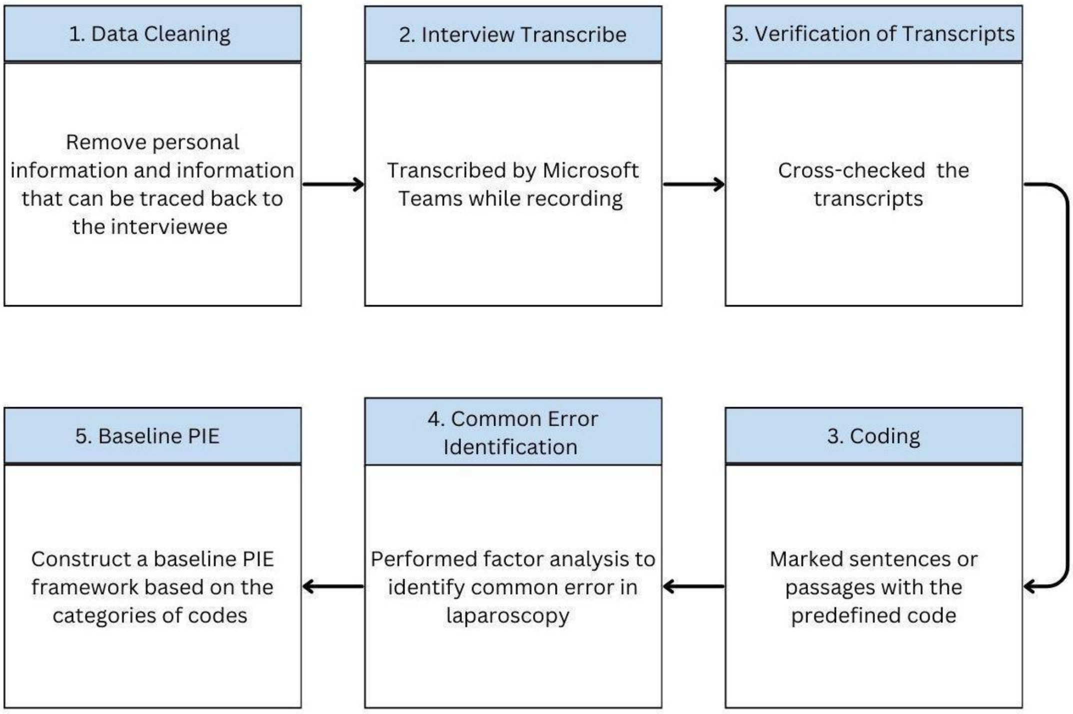
Note. The “PCEI” refers to Problem centred experts interview. The “SMEs” indicate subject matter experts.

2.2.7 Data analysis

Data analysis has been organised into multiple steps (View Figure 2). Data cleaning was performed to ensure the removal of personal information and specific information such as interview dates and times from the transcript. The problem-centred-expert-interviews were transcribed verbatim by Microsoft Teams. Following this, a verification process was undertaken where transcripts were cross-checked by simultaneously listening to the recording and reading the text to ensure accurate transcription. The interview was subsequently analysed using qualitative content analysis (Graneheim & Lundman, 2004). The collected data were coded using predefined codes to determine the common error in laparoscopy among intermediate surgeons based on MIS experts' training experience. In the next step, sentences and passages in the transcript concerning error identification were marked and coded into four categories. Detailed coding criteria can be found in the coder manual (see Appendix A). Additionally, any pertinent information that did not align with the codes but contributed to the overall framework was organised in bullet points. A frequency analysis was conducted to identify common errors performed by intermediates based on the rating of most to least common errors provided by SMEs, shedding light on common error occurrences. This will deliver two primary pathways in error identification patterns by combining the most common error mentioned by the interviewee and based on the literature review mentioned above. In the final step, a base model was developed based on the four identified categories of loop error identification patterns in laparoscopy.

Figure 2

Visualisation of Data Analysis



2.3 Result

2.3.1 Subject Matter Experts Demographic

Table 2 demonstrated the demographic characteristics of subject matter experts.

Table 2

Demographic of Subject Matter Experts

	SME 1	SME 2	SME3	Median
Time in practice (years)	30	9	12	17
Fellowship focus	Robotics and Minimally invasive surgery	General and Laparoscopy	Pancreaticobiliary	-
Length of interview (minutes)	41:18	34:04	43:06	39:29
Intermediate training experience	Yes	Yes	Yes	-

Note. The "SME" indicates to Subject Matters Expert

2.3.2 Frequency Analysis of Common Errors in Laparoscopy

As shown in Table 3, it is evident that spatial disorientation is most frequently mentioned error performed by intermediate-level surgeons, as identified through the training provided by experts. It was observed in two out of three SME interviews as the most common error.

Table 3

Frequency Analysis of Common Error

SME	1 (Most common error)	2	3	4 (Least common error)
1	Spatial disorientation	Overshooting with instruments	Excessive force	Steering of instruments
2	Spatial disorientation	Non-Dominant Hand Coordination Deficiency	Excessive force	Omission and commission
3	Conflicts of instruments	Spatial disorientation	Omission and commission	Excessive force

2.3.3 Coding of Interview

The analysis of the collected data resulted in four patterns in error identification in laparoscopy. These patterns showed how an error is detected, evaluated, labelled and recovered.

2.3.3.1 Error Detection

This pattern refers to the process of identifying deviations of stimuli that could potentially lead to negative consequences for the patient's safety and recognising this deviation as an error. In laparoscopic procedures, error detection can be triggered by several factors, including patient outcomes, performance parameters, supervisor's feedback and self-awareness.

Patient Outcomes. According to the SMEs' in this study, intermediates often become aware of errors through suboptimal patient outcomes. When a patient outcome deviates from expectations, intermediates are prompted to investigate and identify the underlying causes of these adverse outcomes. This process involves tracking back to the specific actions or stimuli that led to negative results, allowing intermediates to focus on improving their performances. Two out of three SMEs explained how patient outcome trigger intermediates to detect errors:

> "*You [The intermediates] operate without any blood loss without any errors. So if you [The intermediates]get proficient in a certain area of that surgery, for example your [The intermediates] technical skill, then you can become proficient in the cognitive skill or in the complete procedure itself.* (SME 2)*"*

> "*Train harder to get better, but also I can relate the score to the outcome of the patients.*(SME 3)*"*

Performance Parameters. Simulation exercises provide objective feedback on an intermediate's performances. By reviewing performance metrics and simulation results, intermediates can pinpoint specific areas where errors occurred and make necessary adjustments. SME 1 highlight the importance of performance parameters in error detection:

> "*One professor teaches and there's multiple students because there are multiple simulators, and at the end of the day, they [The intermediates] look at the data of the simulator and also the teacher combines what they saw, and that's the progress*."

Furthermore, SME 2 responded :

> "*It's a way to improve it by using that left hand, but all those things you [The interviewer] said, those are the parameters we do research with*".

Supervisor Feedback. This factor triggers error detection, particularly when supervisors observe errors made by intermediates and provide indirect feedback. Instead of explicitly labelling specific errors, supervisors offer general suggestions for improvement. This approach of indirect feedback prompts intermediates to engage in reflective practice, particularly by reviewing their simulation performance. Two out of three SMEs explained the role of supervisor feedback in error detection:

"*your [The intermediates] supervisor can provide you with that feedback on something is wrong* " (SME 2)

" *Yeah, I'm not doing it normally, but if I see something not going well and I want them to learn it, then I tell them."* (SME 3)

Self- awareness. Self-awareness involves the participant's ability to recognise both intended and unintended actions that lead to negative outcomes during and after the laparoscopy. This self-reflective process enhances the ability to detect errors through participant's awareness of their performances and their impact on patient outcomes. Self-awareness allows intermediates to recognise and evaluate their action in real-time. By being attuned to their performance, they can identify whether an action was intended or unintended and understand how it contributes to positive or negative outcomes. SME 1 described how self-awareness of intermediates triggers error detection during the laparoscopy procedure:

"*I know it's somewhere there, so they [The intermediates] start with pointing the instrument already in that direction, and then they also look at the endoscope, because the endoscope is looking at the target. So apparently that is the direction, so you [The intermediate] start correcting by official clues."*

Similar explanations were mentioned by SME 3:

"*they [The intermediates]will sense that, but they will proceed because they don't know how to uh. Uh, perform this task without this conflict of instruments*."

However, two out of three SMEs explained that self-awareness can also trigger error detection after the procedures. Post-operative reflection enables them to identify patterns and specific actions that need improvement to reduce errors in laparoscopy performance.

"*You [The intermediates] have to think after, but what do I have to improve? And then you suddenly see it, and maybe even in your head."* (SME 2)

"So they [The intermediates] sense themselves. Oh if I do this then it goes better next time. Also, uh, when they watch a more expert person, they will see. I have always this conflict of instruments and they don't. What are they doing?" (SME 3)

2.3.3.2 Error Evaluation

These patterns indicate that the process begins with the surgeon recognising an error and comprehending its significance and potential impact on patient safety and surgical outcomes. In other words, errors are effectively "mapped" within the surgeon's cognitive framework. This is demonstrated in Figure 3, F. All SMEs explained how error recognition occurs when intermediates encounter surgical stimuli that have negative impact on patients:

" They [The intermediates] have trouble finding back to direction or find the direction" (SME 1)

" I was grabbing the tissue, and it was wrong" [saying from intermediates perspective] (SME 2)

"And sometimes your [The intermediates] instrument is in the line of you. You can't see well what you're doing" (SME 3)

2.3.3.3 Error Labelling

In this pattern, the process unfolds after the surgeon detects a specific stimulus as an error and classifies it accordingly. In other words, the surgeon designates a particular action as an error based on its adverse implications for patient safety. See Figure 3, path G. All SMEs elaborated on the process of error labelling:

"they [The intermediates] let slip the tissue that they have trouble in holding up to tissue" (SME 1)

"no major complications like bile, about the bile duct leakage or or or big bleedings." (SME 2)

"performed conflict of instrument if you [The intermediates] work in the abdomen and small intestine gets stuck by two instruments, then you can injure the intestinal wall." (SME 3)

2.3.3.4 Error Recovery

This pattern refers to the situation in which the surgeon effectively detects errors during laparoscopic surgery and promptly develops and applies strategies to address and recover from the labelled errors. Error recovery occurs too in the pattern of error identification among intermediates, see Figure 3, E and I. Error recovery is influenced by two primary types of factors: external factors, such as supervisor feedback, and internal factors, such as self-regulation.

Supervisors Feedback. Supervisor feedback, where intermediates receive direct feedback and clear instructions for performance adjustments during training sessions, is an example of external feedback. Two out of three supervisors SMEs explained how direct supervisor feedback is involved in error recovery:

"There I was. I tell them, So if you change an instrument, you have to bring it back in position" (SME 1)

"I tell them [The intermediates], listen, we see on the computer to analyse your work, that you have to work on the economy of motion and you can do that by simulator training" (SME 3)

Self-regulation. This internal factor refers to the ability of an individual to independently monitor, evaluate, and adjust their performance to correct errors and improve future outcomes. All SMEs contributed perspectives on how self-regulation initiates error recovery:

> *"They aware of the fact that they can correct or they can influence those factors while operating, and they should do so now."* (SME 1)

> *"Students [The intermediates] suddenly aware of the error and adjust, even I experience myself."* (SME 2)

> *"They [The intermediates] get become aware of their own mistakes. This is a sense. This task is not going well."* (SME 3)

Upon being questioned about effective recovery strategies for intermediates to reduce tissue damage, the SMEs outlined two techniques namely, mental analysis and simulation training.

Mental analysis. This technique involves participants mentally formulating recovery strategies based on their implicit knowledge to reduce tissue damage. Two out of three SMEs explained how the mental analysis technique is applied in developing recovery strategies:

> *"... lead to small errors in the surgery. ... what is important, besides training maybe to .... get an idea of awareness, ... before ....the surgery you [The intermediates] can say to yourself or say to your supervisor ..... focus on using my both hands ..... focus on and the right amount of traction to the tissue or I want to open, because this."* (SME 2)

> *"I think a very quick mental analysis takes place of why does this mistake happen, and what tricks do I have in my toolbox to to overcome this?"* (SME 3)

Simulation Training. This technique involves participant returns to simulator-based training to improve technical skills with the objective of decreasing certain error performance. Two out of three SMEs provided insights on how simulator training took place in reducing error performances:

> *"I think it's relevant to talk about a step-wise training on simulator.*
> *So first, you [The intermediates] start with that yeah, and that I mean, along the way, you learn more technical skills, you get proficient."* (SME 2)

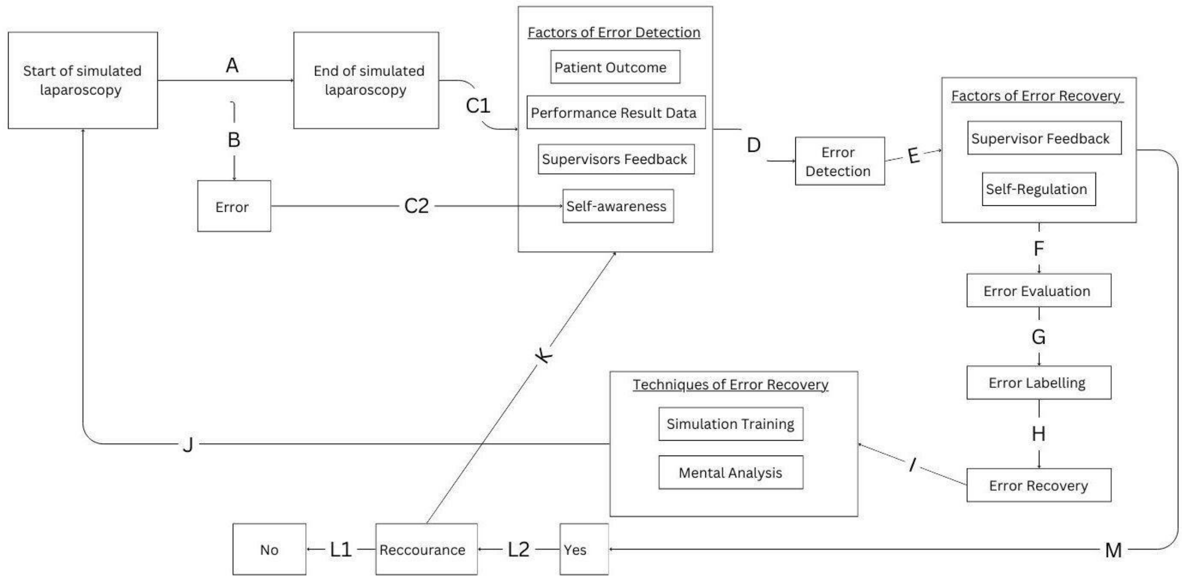
> *"Very intense training in an abstract environment like that simulates provide that keeps them [The intermediates] away from thinking about the appendix or the gallbladder or the column."* (SME 3)

2.3.4 Conceptual Framework of Pattern of Identifying Errors

Based on the PCEI, the patterns of identifying error in simulated laparoscopy were formulated. As illustrated in Figure 3, surgical errors may occur during laparoscopic procedures (see A & B). Upon the occurrence of an error, intermediates are capable of detecting it either upon completion of surgery (C1) or during the procedures itself (C2). This detection subsequently activates their cognitive error detection process, thereby prompting reflection on the underlying issues (D), which is the first pattern of error identification. Following this, the detection of error triggers various factors associated with error recovery, facilitating intermediates in investigating the actions that led to the error during the laparoscopy (E). These factors may function either in conjunction or independently, leading intermediates to assess the potential causes of the errors (F). Upon identifying these causes, intermediates proceed to label the specific actions performed (G) and analyse the rationale behind these errors (H). These demonstrate the second and third patterns of error identification. Subsequently, intermediates apply the error recovery strategies they have formulated, application of these techniques can be done independently or synergistically (I). These strategies are then applied in subsequent surgical procedures (J). After the implementation, intermediates evaluate whether the error has recurred (K). The strategy is deemed successful if the error does not recur or shows a reduced likelihood of recurrence over time (L1). Conversely, if the error persists or recurs in the short term (L2), intermediates revert to step E (M) to refine and adjust their strategies.

Figure 3

Visualisation of Patterns of Identifying Errors Framework



2.3.5 Error Identification Patterns of Excessive Force

The PCEI offered valuable insights into the patterns of error identification associated with excessive force during laparoscopic procedures. SME 2 provided an experienced-based example highlighting the conditions under which intermediates applied excessive force on instrument handling in laparoscopic surgery. According to SME 2, error detection is the first pattern of error identification demonstrated by intermediates when they perform an excessive force:

"*If you [The intermediates] have the path length of the left and the right hand, ..have efficient use of both instruments, but it's completely true what the other laparoscopic surgeon said, because if you don't use it the right way, you don't have optimal efficiency…*"

The second patterns demonstrated is error evaluation:

> *"Effective traction... makes that you can apply the right amount of force that you don't have eating a steak with one knife will have to generate more force...*"

This progression leads to the third pattern, namely error labelling:

> "*...excessive force and depth perception that is also the... errors overshooting the target and therefore applying too much force to different tissue…*"

Subsequently, the intermediates employ the technique of mental analysis to cognitively map out error recovery strategies by understanding the causes of excessive force and its consequences.

> "*Therefore applying too much force to the different tissue … result unwanted damage to tissue.*"

2.4 Discussion

This study aimed to establish a conceptual framework for the Patterns of Identifying Errors (PIE) Framework , focusing on understanding the errors made by intermediate practitioners during the early learning phases of laparoscopic surgery. To achieve this, a qualitative research design was implemented, involving problem-centred expert interviews (PCEIs) with subject matter experts (SMEs) in laparoscopy. The study investigated common errors and explored patterns of error identification and strategies for error recovery, particularly emphasising the role of excessive force in tissue damage among intermediates during their early learning phase.

The frequency analysis result in Table 3, concluded that spatial disorientation is another common error encountered in the early learning phase of intermediate surgeons. This error involves the difficulty surgeons face in accurately perceiving and interpreting the visual environment within the simulated training setting for laparoscopy. These findings are consistent with Bonrath et al. (2015) and Tang et al. (2004). Bonrath et al. (2015) noted that spatial disorientation is a frequent error, emphasising that poor visualisation can lead to improper tissue grasping and subsequent damage. Similarly, Tang et al. (2004), demonstrated that laparoscopic surgeons often struggle to correctly orient surgical instruments relative to tissue planes, resulting in ineffective tissue splitting. Both studies highlight the critical importance of clear and accurate visual feedback in laparoscopic procedures. In conclusion, spatial disorientation, alongside excessive force, emerges as a prevalent error in the early learning phase. These findings offer two distinct error pathways that can help further investigate the cognitive and motor processes associated with errors and error recovery in laparoscopic performance within a simulated experimental setting (see Chapter 3).

The study identified several cognitive process patterns in error identification during laparoscopic procedures, which shed light on how errors are detected, evaluated, labelled, and recovered by intermediate practitioners. The first pattern was Error Detection, where intermediates identify deviations in stimuli that may lead to adverse patient outcomes. Similar findings were reported by Satava (2005), indicating that laparoscopic surgeons enhance the likelihood of correcting errors and minimising patient impact by first detecting the specific type of error they have made.

Patient outcomes, performance parameters, supervisor feedback, and self-awareness are critical factors that trigger intermediate to detect errors within simulated laparoscopy. For example, patient outcomes often serve as a trigger for intermediates to identify underlying errors, while simulation exercises provide objective feedback that helps pinpoint specific errors. Supervisor feedback, typically indirect, prompts intermediates to engage in reflective practice, and self-awareness allows them to recognize and correct their actions in real time or during post-operative reflection.

Second pattern identified in this study was Error Evaluation, where intermediates recognize and understand the significance of an error and its potential impact on patient safety. This recognition occurs when practitioners encounter surgical stimuli that negatively affect patients, leading to the "mapping" of these errors within their cognitive process.

The process of Error Labelling follows, where the surgeon classifies a specific action as an error based on its adverse effects on patient safety. This step involved a clear labelling and categorisation of errors, which is essential for subsequent correction and learning. While no existing studies specifically support this pattern, it remains a critical component of understanding error performance and improvement in laparoscopy practice.

The last pattern, Error Recovery refers to the strategies that surgeons develop and apply to address and correct detected errors during surgery. Recovery is influenced by both external factors, such as direct supervisor feedback, and internal factors, like self-regulation. The role of supervisor feedback as an external factor is aligned with Strandbygaard et al. (2013) and Bjerrum et al. (2015). Similar findings were reported by Strandbygaard et al. (2013), highlighting the essential role of direct supervisor feedback in enhancing the effectiveness of error recovery during training. Likewise, Bjerrum et al. (2015) demonstrated that supervisor feedback offers novices critical insights into areas requiring revision, thereby enhancing their efficiency during simulator training. Effective recovery strategies highlighted by SMEs include mental analysis, where intermediates mentally formulate recovery strategies, and simulation training, which enhances technical skills to reduce error performance. Aligned with Satava (2005), this indicates that simulators can effectively "teach" surgeons how to identify errors and develop strategies for recovery. These patterns emphasise the complex and dynamic nature of error identification in laparoscopic surgery and underscore the need for targeted training programs that address these specific areas to enhance surgical performance and patient safety.

Based on the findings, a PIE Framework in laparoscopic procedures was developed. This framework outlines the stages involved in detecting, analysing, and recovering from laparoscopy error, as demonstrated in Figure 3. Additionally, the evidence provided by SME 2 supports the notion that excessive force contributes to tissue damage. This finding is aligned with the PIE Framework, underscoring the cognitive process on how intermediates identified excessive force.

2.4 .1 Limitations and Recommendations

A limitation of this interview study is that it exclusively interviewed SMEs in the Netherlands. This geographic focus restricts the scope of the findings, as practices, training environments, and error patterns can vary significantly across different countries. Variations in healthcare systems, educational methodologies, and cultural factors may influence how errors are identified and managed in other regions. Consequently, the insights gained may not be fully representative of global practices or applicable to settings outside the Netherlands.

For example, in Japan, laparoscopic training often involves a technique called Laparoscopic Origami, where surgeons practise folding specific designs using origami paper with laparoscopic graspers. This method typically involves filming the surgeon's performance rather than relying on objective performance metrics provided by simulators. According to Noda et al. (2024), this approach does not incorporate performance parameters in the same way as the simulator-based training we have proposed. Consequently, performance metrics are not recognized as factors in this training method.

Moreover, in Taiwan, training is typically conducted in group settings where one trainee performs while others observe. During this process, peers may offer feedback if they choose to do so. This peer feedback could potentially influence error detection and recovery, a factor not currently addressed in the PIE Framework. Therefore, it is suggested to explore training practices or to interview SMEs from different countries to better refine the current PIE model. By examining diverse training environments and feedback mechanisms, such as the peer feedback observed in Taiwan, the model can be enhanced to address various factors influencing error detection and recovery more comprehensively.

Another limitation is that the cognitive processes of intermediates are not mapped within the current framework. The framework is constructed based on observable behaviours performed by intermediates and observed through SMEs, but it lacks a comprehensive understanding of the inner mental analysis involved in how errors are fully understood and identified. As Satava (2005) suggested, intermediates often reduce errors as they engage in cognitive processes and develop a deeper understanding of the full scope of the error. Future studies are suggested to integrate cognitive analysis into the framework to better capture how intermediates mentally process and refine their error identification and recovery strategies. This would provide a more complete picture of error management and improve the effectiveness of training methodologies.

2.4.2 Conclusion

This study successfully developed the Patterns of Identifying Errors (PIE) in simulated laparoscopic procedures, highlighting cognitive process patterns namely, error detection, evaluation, labelling, and recovery. Findings underscore the significance of spatial disorientation and excessive force as common errors in the early learning phase. Notably, excessive force was identified as a critical factor leading to tissue damage, further emphasising the importance of precise instrument handling. The study also emphasises the critical role of supervisor feedback and cognitive processes in effective error management. However, limitations include the focus on a geographically restricted sample and the lack of integration of cognitive processes into the current framework. Future research should broaden the geographic scope and incorporate cognitive analysis to enhance the PIE model and training methodologies, providing a more comprehensive approach to improving laparoscopic performance and patient safety.

3. Experiment study

3.1 Introduction

Through the PECI and previous literature review, excessive force and visual disorientation are two prevalent errors that often arise during the early learning phase in laparoscopy among intermediates under simulated based training. Both of these errors can significantly impact performance outcomes, and their identification and correction are essential to reducing tissue damage. These two errors present distinct methodological pathways for evaluating the validity of the proposed Patterns of Identifying Error (PIE) Framework demonstrated in Figure 3.

Tissue damage in simulated laparoscopy tasks is likely to occur due to applying exercise force on the instruments, which might be caused by inefficiency motor actions or muscle control. One way to explore this hypothesis is by examining the muscle activity and its relation with tissue damage. Electromyography (EMG) serves as an effective tool for measuring motor muscle activity in the hands and forearms during surgical procedures. While most studies utilise EMG to assess the ergonomic aspects of instrument design in laparoscopy (González et al., 2020; Sancibrian et al., 2020), they also confirm EMG's utility in objectively evaluating muscle control. Matern et al. (2004) identified several muscles relevant for EMG measurement in laparoscopic instrument handling; however, this study focuses exclusively on the flexor carpi radialis (FCR) and Brachioradialis (BR) due to their critical role in motor learning and control. The selection of the FCR is based on its capacity to provide valuable insights into fine motor skills and reflex responses during repetitive training sessions (Thompson et al., 2018).

Synchronised activity is crucial for ensuring stability and effective control during movements (Latash, 2018; Ateş et al., 2018). Muscle coactivation refers to the coordinated action of agonist and antagonist muscles to maintain motor control and joint stability (Latash, 2018). In these antagonistic pairs, one muscle contracts while its counterpart relaxes, facilitating precise joint movement (Jones & Round, 1990). Muscle co-activation is commonly interpreted in terms of its impact on movement speed and stability. This effect is mediated through alterations in the stiffness-like properties of the muscles and their capacity to generate resistive forces per unit of displacement (Latash, 2018)

Several studies have demonstrated that a decrease in muscle co-activation reflects a learning process (Franklin et al., 2003; Huang et al., 2012). Muscle co-activation initially increases but subsequently decreases as learning progresses (Franklin et al., 2003). In addition, Darainy and Ostry (2008) demonstrated that post-learning co-activation differs systematically depending on force levels and movement direction. The co-activation of muscles becomes more targeted and efficient as motor skills develop (Hall et al., 1994). In other words, within the simulated laparoscopic training setting, increased muscle co-activations at the beginning of training indicates that the surgeon is still in the process of learning. A subsequent decrease in co-activation over time suggests that the surgeon is adapting and refining their skills, becoming more proficient in performing laparoscopic procedures.

This exploratory study aims to answer the question " *Does a reduction in muscle co-activation over time lead to increased stability and more effective movement, thereby reducing tissue damage in simulated laparoscopic procedures?*" In expectation, muscle co-activation ration will move towards zero throughout the trials, reflecting enhanced stability and more effective movement control with forceps, thereby resulting in decreased tissue damage. This approach allows for a more nuanced analysis of muscle activity and its impact on performance.

3.2 Method

3.2.1 Participants

Three participants agreed to participate after voluntary sampling via email invitation. However, one participant withdrew after experiencing motion sickness while interacting with the LapSim simulator. Consequently, the final sample consisted of two participants: one male and one female, both right-handed, with an average age of 24.5 years (*SD* = 0.5). Both participants were enrolled in the Technical Medicine program at the University of Twente, at levels ranging from third-year bachelor's to PhD students. As an incentive, participants were offered a chance to win a €25 Bol.com voucher in appreciation for their participation.

3.2.2 Ethical Approval

Ethical approval for the current study was granted by the Natural Sciences & Engineering Sciences at University of Twente, under reference number 240299.

3.2.3 Design

This study employed a within-subject design with a co-activation ratio of left and right hand as the dependent variable. The independent variable in this study was the trial condition.

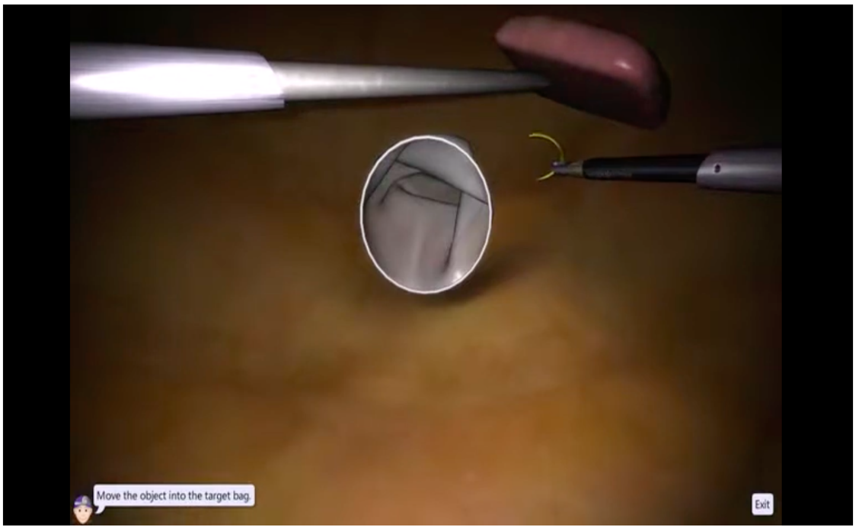
3.2.4 Instruction and Scenarios

The experimental design included 30 trials. This study involved participants performing a simulated laparoscopic task, specifically the “Grasping and Lifting” task from the “Basic Skills Short Course - Difficult” segment of the Technical Medicine course. The task comprised three sequential steps: first, the participant used a probe instrument to lift a square-shaped object, revealing a needle. Next, the participant employed a grasper to pick up the needle, and finally, the needle was deposited into a surgical bag. Participants received instant feedback on task completion through a “little helper” indicator located at the bottom left corner of the screen (See Figure 4).

Each task was allocated a maximum duration of four minutes and involved two distinct control conditions: Left Probe & Right Grasper and Right Probe & Left Grasper. In the Left Probe & Right Grasper condition, participants controlled the probe with their left hand and the grasper with their right hand. Conversely, in the Right Probe & Left Grasper condition, participants used their right hand for the probe and their left hand for the grasper. Each participant sequentially performed each control condition seven times per trial, amounting to a total of 14 method switches.

Figure 4

Lifting and Grasping Task



3.2.5 Apparatus

Laparoscopy Simulator

This study employed the LapSim© virtual reality simulator located at the TechMed Simulation Centre (TMSC) at the University of Twente, Netherlands. This simulator incorporates two forceps tools that participants used to manipulate the graspers and other instruments within the virtual laparoscopy environment (refer to Appendix B, Figure B1).

The participant interaction with the simulated environment was facilitated by the Virtual Laparoscopy Interface (VLI) hardware, with LapSim© Basic Skills v3.0 serving as the training software. The simulator is composed of three SimBall modules, where the grasping instrument is inserted on the left, the probe on the right, and a camera instrument in the centre (see Appendix B, Figure B2). These tools resemble actual surgical instruments, excluding the forceps at the tip. The modules are capable of sensing the angle of insertion and the extent of instrument manipulation. These movements are then translated and displayed on a Dell 23-inch monitor (Model P2314Ht). Previous research has demonstrated the effectiveness of LapSim in assessing laparoscopic skills and providing trainees with immediate feedback (Elessawy et al., 2021).

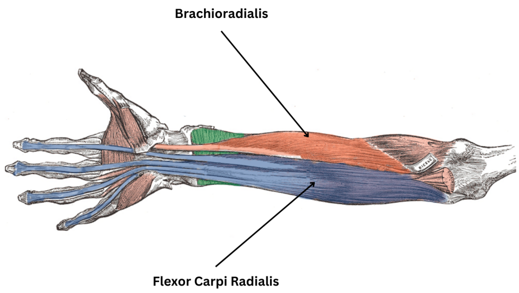
Electromyography Machine

The study employed the TMSi Porti 7 electromyography (EMG) machine to record muscle activity generated by the Flexor Carpi Radialis (FCR) and Brachioradialis (BR) of both hands of the participants during the simulation task (See Figure 5 and Appendix B, Figure B3). Although the machine is equipped with 16 channels, only four channels were utilised for this experiment, with a sampling rate of 128 Hz (View Appendix B, Figure B4). The EMG signals were interfaced with an HP Pavilion 16-eg2980nd laptop, which features a 15.6-inch monitor, while the Polybench 5 system was employed for visualising and recording the signals (See Appendix B, Figure B5). This setup enabled detailed real-time monitoring and documentation of the EMG data.

3M Red Dot ECG electrodes (Type 2560) were affixed to the skin to measure muscle electrical activity. Two approaches were used to mitigate noise in the EMG signals. The first involved activating the high-pass filter on the Poly Bench 5 system to remove low-frequency interference. The second involved securing the lead wires with surgical tape to prevent movement and maintain signal stability.

Figure 5

Visualisation of Flexor Carpi Radialis and Brachioradialis



3.2.6 Materials

Task & Time Tracker

A Task & Time tracker form was designed to keep track of the completed task and duration of each scenario and task (see Appendix D).

Experimenter Manual

To ensure the experiment was conducted as organised and with standard, an experimenter manual was developed. The manual includes detailed experiment setup instructions for the TMSi porti 7 and LapSim simulator. Additionally, a verbal introduction script was included, with which this experimenter can verbally explain the outline of the experiment, including the research aim, duration of the experiment, and several points that participants need to be aware of before, during and after the experiment (see Appendix C and Figure B6 in Appendix B).

3.2.7 Procedure

Prior to participation, participants were briefed on several key points. They were instructed to refrain from alcohol and caffeinated beverages for 24 hours before the experiment to ensure optimal physiological conditions. Additionally, participants were advised to shave or remove arm hair to minimise discomfort during electrode removal, thereby improving adhesion and the accuracy of readings. Participants were also recommended to wear short-sleeve shirts and to remove any hand or arm jewellery to facilitate electrode placement and mobility. Furthermore, individuals with a history of motion sickness or those who experienced discomfort during the study were advised to either refrain from participation or notify the research team if they began to feel unwell. Upon arrival, participants were warmly greeted and provided with verbal instructions outlining the experiment's overview. This introduction included informing participants of their rights, including the ability to withdraw from the study at any time. It was emphasised that the study would involve collecting their physiological data, such as muscle activity and voice recordings, during the think-aloud component. An example instruction was provided to ensure participants understood the think-aloud method and how to verbalise their thoughts while performing the laparoscopic task.

Participants were advised to remove any jewellery from their arms and wrists before the session and were informed of the potential for experiencing motion sickness due to the 3D simulated laparoscopic environment. To minimise discomfort, they were advised that they could pause the experiment at any time to take breaks. Once participants confirmed that they had no questions, they were asked to read and sign the informed consent form.

Following the completion of the informed consent form, participants received detailed instructions for connecting to the EMG machine. Subsequently, participants were directed to perform specific actions to identify the two target muscles for this study. Detailed procedures are outlined in the experimenter manual located in Appendix C. Alcohol pads were used to cleanse the skin and reduce any potential interference. Electrodes were then applied to the participant's FCR and BR on both hands. Finally, participants were guided to the LapSim simulator for the continuation of the experiment. Participants then proceeded to perform the task on the LapSim simulator while verbalising their thoughts that were recorded by the Zoom (H4N Pro) (See Appendix B, Figure B3). However, the data were discarded and not included in further analysis.

To prevent fatigue, participants were encouraged to take a break after completing 15 trials. Once participants completed all scenarios, they were warmly thanked for their participation and were again provided with contact details in case they had questions in future. Visualisation of the procedures is in Figure 6 and full experiment set up in Figure 7.

Figure 6

Visualisation of Experiment Procedure

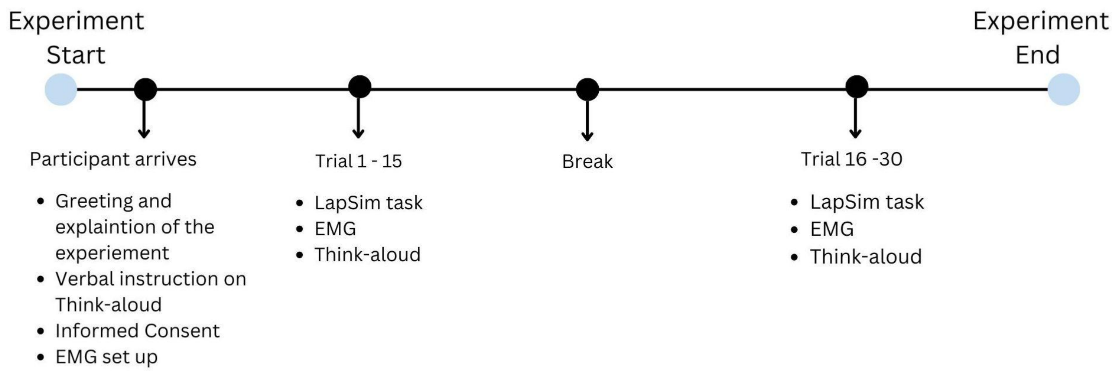


Figure 7

Full Experiment Set up

Note. The participant has provided consent for the use of the picture.

3.2.7 Data analysis

In this study, data were collected from electromyography (EMG), the LapSim simulator, and the think-aloud protocol. However, due to time constraints, the analysis is currently limited to the EMG data. The following steps were undertaken to analyse the EMG data. Initially, data pre-processing was conducted to prepare the EMG data for analysis. Although noise removal is typically essential in EMG processing, the use of a high-pass filter during data recording rendered this step unnecessary. Subsequently, data cleaning was performed to isolate relevant data, specifically focusing on muscle activity recorded during task performance.

Co-activation calculation

The next step is to calculate the coactivation of muscles. The calculation of the co-activation ratio followed a systematic process. Each trial was divided into four equal quarters, with each quarter lasting one minute. For each quarter, the average muscle signal was calculated, resulting in four average muscle signals per trial. These four averages were then combined to compute an overall average EMG value for each muscle group across the entire trial. This process yielded four overall average values per trial: one each for the left agonist, right agonist, left antagonist, and right antagonist. Finally, the co-activation formula was applied to determine the co-activation ratio for both the left and right hands. The co-activation ratio between the agonist and antagonist muscles was analysed using the formula from Begalle et al. (2012), which involves dividing the normalised EMG activity of agonist and antagonist. According to this formula, if the result is closer to zero, it can be said that there is more co-activation, reflecting more stability. If the result is more than zero, it means that the movement performed has a greater intensity for the antagonist muscle. Conversely, if the result of the formula is less than zero, it means that the movement is dominated by the agonist muscle.

Trend analysis

To examine the trends in muscle co-activation, a detailed trend analysis was performed on the EMG data using R Studio (version 2023.06.0+421) (View Appendix E). This analysis focused on identifying patterns and changes in the co-activation levels of muscle groups throughout the trials by participants. Individual trend analyses were performed for each participant due to the variation in the number of trials completed. Participant One completed 30 trials, while Participant Two completed 27 trials due to personal circumstances. To account for this discrepancy and ensure accurate and meaningful analysis, it was necessary to analyse the trends in muscle co-activation separately for each participant.

3.3 Result

Table 4

Demographic statistical of Participants

Participant No.	Gender	Age	Dominant Hand	Number of trials completed
1	Female	24	Right	30
2	Male	25	Right	27

3.3.1 Trend Analysis for Participant One

Participant One exhibited a consistently increasing pattern of co-activation in the left hand across the trials as demonstrated in Figure 8. The co-activation values for this participant ranged from 1.6 to 2, with a mean of 2 (SD = 0.5). Notably, the co-activation pattern began to stabilise by trial 4. Prolonged periods of stability were observed between trials 7 and 13, with the co-activation of 0.8, and reoccurred between trial 19 and 28, where the co-activation increased to 2.3.

As illustrated in Figure 9, Participant One exhibited a relatively stable pattern of co-activation in the right hand. The co-activation ratio for this participant ranged from 0.5 to 1.6, with a mean of 0.6 (SD = 0.2). A reduction in co-activation was observed as the muscle activity decreased throughout the trial. Specifically, from trials 7 to 15, the co-activation remained stable at an average of 0.8, indicating minimal fluctuation in muscle activity during this period. Similarly, from trials 16 to 23, the average co-activation was 0.7, and from trials 24 to 30, it further stabilised at 0.6.

Figure 8

Left Hand Co-activation Across Trials of P1

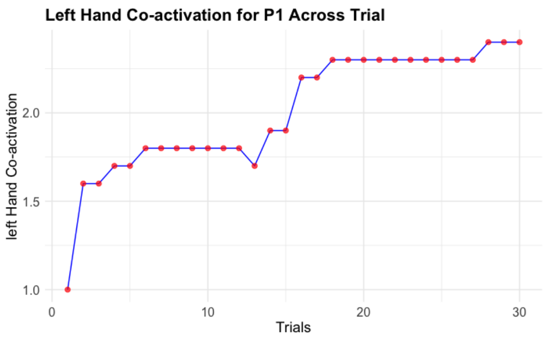
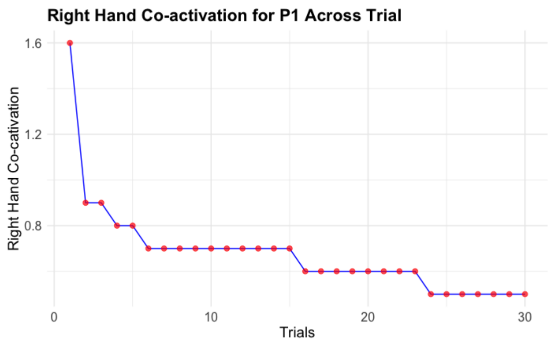


Figure 9

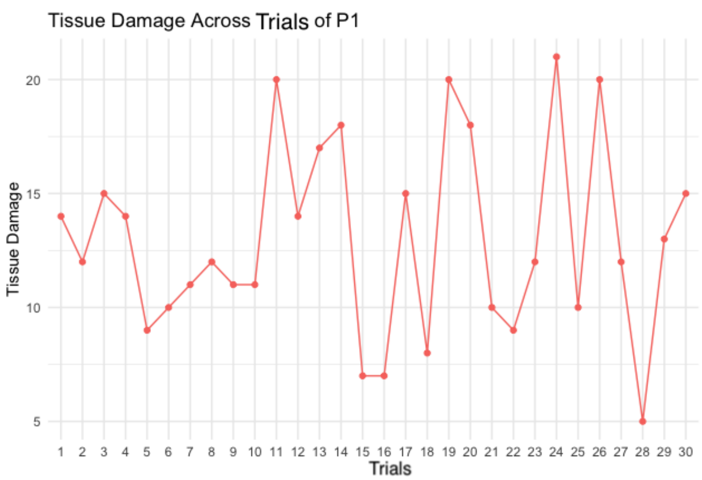
Right Hand Co-activation Across Trials of P1



Tissue damage decreased throughout the trials; however, the reduction was relatively modest (See Figure 10). The pattern of tissue damage demonstrated fluctuations throughout the trials. For Participant Two, tissue damage ranged from 5 to 21 (*Mean* = 14, *SD* =3.6). During trials 9 through 10, tissue damage consistently occurred 11 times. A comparable pattern was observed between trials 15 and 16, during which tissue damage also remained constant at 7 times. The peak of tissue damage is at trial 24 with 21.

Figure 10

Visualisation of Tissue Damage and Trial of P1



3.3.2 Trend Analysis for Participant Two

Participant Two demonstrated a consistent decline in co-activation of the left hand throughout the trials, as illustrated in Figure 11. The co-activation values for this participant ranged from 1.4 to 88.4, with a mean of 10.3 (*SD* = 86.9). Following trial 18, the co-activation patterns began to stabilise. Although there was an initial decrease in co-activation, the levels gradually increased over time, leading to a more consistent pattern.

As illustrated in Figure 12, Participant Two showed a relatively consistent co-activation pattern in the right hand. The co-activation ratio ranged from 0.4 to 51, with a mean of 5.9 (*SD* =10.5). There was a noticeable decline in co-activation as muscle activity diminished, with a decrease from 3.5 in trial 5 to 1.5 by trial 10. From trial 11, there was a gradual increase in co-activation to 2.9, but this increase was relatively small.

Figure 11

Left Hand Co-activation Across Trials of P2

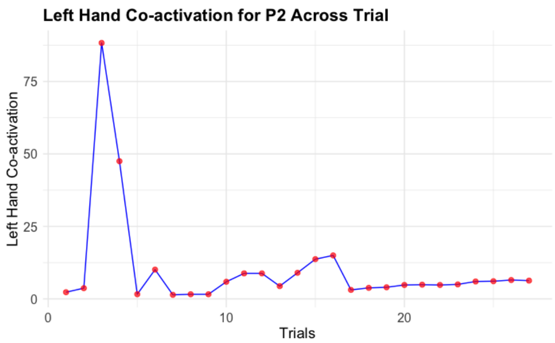


Figure 12

Right Hand Co-activation Across Trials of P2

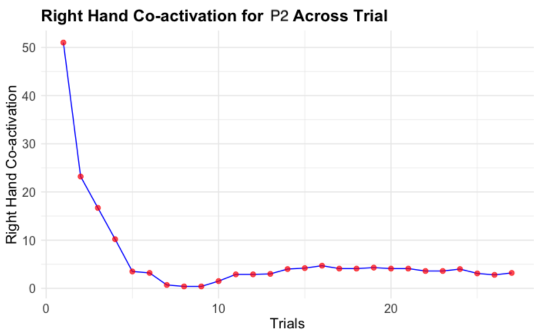
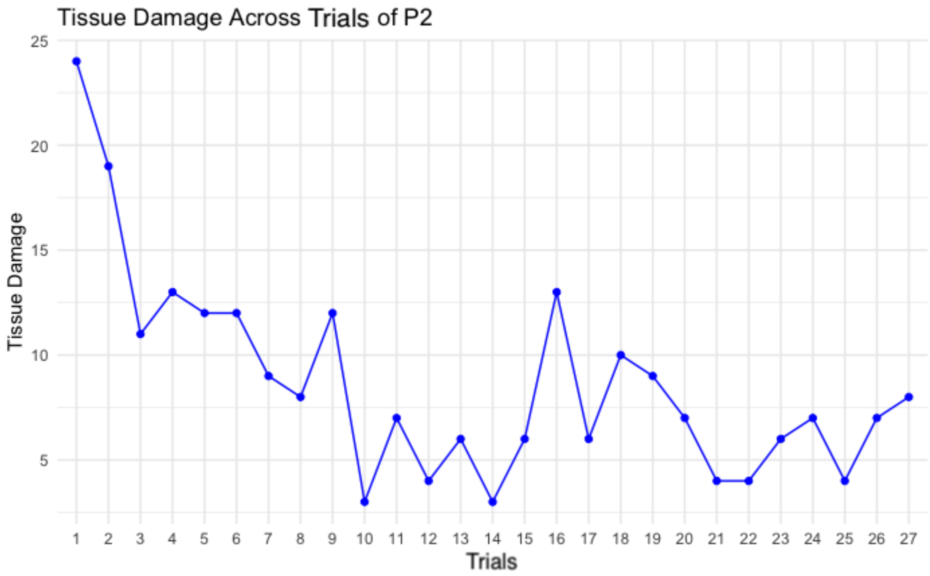


Figure 13, showed a reduction in tissue damage throughout the trials for Participant Two . The tissue damage ranged from 3 to 24 with the average of 7.4 (*SD* = 5). Between trials 18 and 22, a marked reduction in tissue damage was observed, with the frequency decreasing from 10 to 4 times per trial.

Figure 13

Visualisation of Tissue Damage and Trials of P2



3.3 Discussion

Muscle Co-activation

The trend analysis revealed that left hand muscle co-activation ratio patterns deviated from zero across trails, indicating a reduction in the muscle co-activation ratio. This reduction in muscle co-activation suggested that one muscle group exhibited greater dominance while another was more reflexed. Such imbalance in muscle activation implied that the left hand served as the primary control hand for Participant One. In other words, the left hand is the control hand, where it is primarily responsible for controlling the forceps to complete the simulated laparoscopy tasks.

In contrast, the muscle co-activation ration patterns of the right hand showed a trend towards zero across trials, indicating an increase in muscle co-activation. This increase suggested that both muscle groups began to work more synergistically over time. The enhanced co-activation implied that the right hand's muscle maintained greater stability throughout the movements, resulting in a stiffer control mechanism on forceps.

Consequently, the right hand can be considered as the "fixed" hand, with the Participant One utilising it as a stabilising force to exert controlled, steady movements during the task.

The muscle co-activation ratio patterns of Participant Two demonstrated similar trends as in Participant One, although the patterns were less pronounced. For Participant Two's left hand, the trend analysis showed that the muscle co-activation ratio moved away from zero across trials, signifying a reduction in co-activation. This pattern implies that the left hand, being the one used to perform the task, acted as the control hand, with one muscle group being more dominant and the other more relaxed.

On the other hand, the muscle co-activation for the right hand moved towards zero over trials, indicating an increase in muscle co-activation. This suggested that the right hand operated with more balanced co-activation between muscle groups, resulting in greater stability and control. As a result, the right hand exhibited increased stiffness to provide consistent control throughout the trials. However, even though Participant Two's muscle co-activation ration patterns share the same general trend as Participant One, the changes through our trials are more subtle and harder to detect.

Overall, the trend analysis for both participants does not provide sufficient evidence to support a clear relationship between muscle co-activation and tissue damage. The analysis primarily offers insights into how muscle co-activation changes over time, rather than elucidating the specific impact on tissue damage. Consequently, it can be concluded that the muscle co-activation in the right hand increased over time, suggesting that participants learned to control their muscles more effectively, resulting in greater stability. However, the specific factors driving this learning effect, particularly for the right hand, remain unclear. One possible explanation could be related to hand dominance, as both participants are right-handed. This dominance may account for the observed stability in muscle co-activation.

Additionally, the stability of muscle co-activation ratio patterns observed in both participants is particularly noteworthy, considering that the simulated laparoscopy task was bi-manual and required frequent switching between hands. This raises questions about whether the “Grasping and Lifting” task is an appropriate task for exploring this relationship. For instance, Takagi et al. (2020) demonstrated that the dominant hand showed greater muscle stability compared to the non-dominant hand in bi-manual tasks, indicating that bi-manual task can result in stable muscle co-activation ratio patterns. However, their study employed a relatively simple task design, which may not fully capture the complexities involved in simulated laparoscopic tasks. Given the complexity of laparoscopy, which involves multiple interacting factors, a simpler bi-manual task might not provide a complete understanding of muscle co-activation ratio within this specific context. However, Takagi et al.’s findings underscore the importance of considering hand dominance in muscle co-activation studies.

Moreover, the stability pattern observed in both hands might benefit from further investigation through think-aloud data. Analysing participants' verbal explanations of their strategies and mechanisms during the task could offer valuable insights into their cognitive and motor processes for managing stability and control. Moreover, it is important to consider the possibility that data artefacts or limitations in trend analysis might have influenced the results. Further research is needed to explore muscle co-activation in simulated laparoscopy tasks more comprehensively and to determine the impact of hand dominance and task complexity on muscle control.

Tissue Damage

Tissue damage patterns varied significantly between Participants One and Participant Two. For Participant One, as illustrated in Figure 10, tissue damage demonstrated irregular fluctuations rather than a consistent linear decline. This inconsistency in tissue damage trends limits the ability to draw conclusions about the relationship between muscle co-activation and tissue damage, as the data does not reveal a clear, predictive relationship.

In contrast, Participant Two exhibited a more obvious and consistent reduction in tissue damage over the trials. This indicated that Participant Two is learning over time in error performances. However, trend analysis alone does not provide a comprehensive explanation between the relationship of muscle coactivation and tissue damage. It may be beneficial to examine specific time intervals preceding instances of tissue damage to gain insights into the learning curve. Additionally, comparing trials with fewer versus more tissue damage could further explore the muscle co-activation difference. There is also the possibility that Participant One exhibits an irregular learning curve, which deviates from the traditional learning curve.

3.3.1 Strengths and Limitations

One of the key strengths of this thesis is that it is the first to explore the relationship between muscle co-activation and tissue damage within the context of simulated laparoscopy through an electromyography machine, while also examining the associated learning curve. By focusing on these aspects, the research offers a new perspective on how muscle co-activation patterns may influence tissue damage and how participants' skills develop over time. This innovative approach provides valuable insights into the cognitive and motor processes involved in simulated surgical tasks. The study's findings could pave the way for future research, enhancing our understanding of muscle control and error identification in complex surgical environments.

Several limitations of the study should be acknowledged. First, the analysis did not include data from LapSim or think-aloud protocols. These additional data sources could have provided valuable insights into the cognitive aspects of error performance and strategy development. Specifically, analysing think-aloud data might have revealed participants' thought processes, error identification patterns, and the triggers that prompted them to take corrective actions. Furthermore, LapSim data might have offered a more comprehensive view of how participants recognized and responded to tissue damage, potentially shedding light on the specific cues or feedback that influenced their recovery strategies. Despite not including LapSim or think-aloud data, the study still provided valuable insights into muscle co-activation patterns and tissue damage. The focus on these specific aspects allowed for a detailed examination of the interactions between muscle activation and tissue damage, contributing to a clearer understanding in motor processes in simulated laparoscopy training.

Second, the study focused exclusively on two muscle groups: the flexor carpi radialis and the brachioradialis. While these muscles were relevant for understanding co-activation patterns and their relation to error identification, other muscle groups could have provided a more complete picture of muscular coordination and control. Incorporating data from additional muscle groups might have yielded further insights into overall motor control and error management strategies. For instance, investigating muscle fatigue in the forearm muscles during laparoscopy, particularly the flexor digitorum profundus and extensor carpi radialis is crucial as these muscles significantly contribute to grip strength and the execution of precise movements (Quick et al., 2003). Overall, these limitations suggested that a more holistic approach, incorporating a broader range of data sources and muscle groups, could have enhanced our understanding of cognitive and physiological aspects of motor learning and error correction. This thesis further confirmed the role of the flexor carpi radialis and brachioradialis in handling laparoscopic instruments, demonstrating their significance in muscle movement during the procedure. These findings align with the work of Matern et al. (2004), supporting the importance of these muscle groups in effective laparoscopic control.

3.3.2 Conclusion

The current study explored the relationship between muscle co-activation and tissue damage in simulated laparoscopy through electromyography (EMG), offering insights into motor learning and control during simulated surgical tasks. The findings revealed distinct muscle co-activation patterns between participants, with Participant One's EMG data showing a more consistent improvement in motor control compared to Participant Two, suggesting a stronger learning effect.

While the trend analysis provided valuable information about changes in muscle co-activation, it did not offer definitive conclusions about its impact on tissue damage. However, the study demonstrated that EMG can objectively measure muscle co-activation, confirming the role of key forearm muscles in laparoscopic instrument handling and aligning with previous research.

The current study also highlights the importance of considering hand dominance and task complexity in future research on muscle co-activation and motor learning in surgical training. Overall, it lays the groundwork for future investigations that could inform more effective training strategies and improve surgical outcomes in laparoscopic.

4. General Discussion

This exploratory thesis aimed to develop a comprehensive framework, the Patterns of Identifying Errors (PIE) Framework, for identifying and analysing error identification patterns to enhance recognition and improve recovery strategies in laparoscopic procedures among intermediate surgeons. This thesis addressed the central question: "*Which cognitive and motor processes are associated with errors and error recovery in laparoscopic performance when using a simulator?*"

From the problem-centred expert interviews (PCEI) with Subject Matter Experts (SMEs), it was found that spatial disorientation as a prevalent error in the early learning phase of intermediate surgeons, consistent with findings from Bonrath et al. (2015) and Tang et al. (2004). Previous research identified excessive force as a common error in laparoscopy surgery. The PECI framework confirms that visual disorientation is also prevalent. These findings highlight two key error pathways—excessive force and visual disorientation—that can be targeted in experimental studies to improve understanding and performance. Moreover, the PCEI revealed four patterns of error identification: error detection, error evaluation, error labelling, and error recovery. Based on these patterns, the PIE Framework was conceptualised (see Figure 3). The interview study also confirmed that supervisory feedback is an effective error recovery strategy for intermediates in the early phase of laparoscopy training, supporting the thesis's expectations. Furthermore, the study identified two key error recovery techniques: (1) returning to simulation training to address identified weaknesses and (2) conducting mental analysis, where practitioners cognitively plan and strategised to avoid specific errors or incorporate necessary actions. These techniques can be employed during unsupervised training phases. The second study explored the use of electromyography (EMG) to better understand the relationship between muscle co-activation and tissue damage in simulated laparoscopy. The results indicated that muscle co-activation provides insights into muscle control during forceps manipulation. Notably, Participant One exhibited a more consistent improvement in motor control compared to Participant Two. However, with only two participants, drawing definitive conclusions about causation between muscle co-activation and tissue damage is not feasible. Therefore, these findings should be interpreted with caution. This study demonstrated that EMG is effective in capturing objective muscle co-activation, offering valuable insights into how muscle control contributes to simulated laparoscopy performance. Additionally, it revealed that motor control can improve through repetitive practice in simulated tasks.

However, the inability to further support a causal relationship may stem from challenges in synchronising muscle signals. The manual marking of trial start and end points may not have been the most objective or accurate, potentially introducing artefacts or inconsistencies that affect data synchronisation precision. Consequently, a new workflow or improved design for data collection and analysis is recommended for future studies.

Interestingly, the study also identified that learning curves related to reducing tissue damage can be irregular. This suggests that examining specific time intervals before the occurrence of tissue damage could be beneficial. By focusing on these intervals, researchers can better explore variability in learning and identify key moments when participants make significant adjustments or improvements (Gabitov et al., 2020). Such targeted analysis might uncover patterns not visible in overall trends and contribute to more refined training strategies and skill development in simulated laparoscopy. This suggests that examining specific time intervals leading up to instances of tissue damage should be a primary focus for future research.

Additionally, incorporating more sensors or measuring additional muscle groups could offer a more comprehensive understanding of muscle co-activation's role in error performance within the simulated laparoscopy context. The current study utilised the "Grasping and Lifting" task, which might not fully capture the complexities involved. Exploring simpler or alternative tasks could potentially yield more precise information about the relationship between muscle co-activation and tissue damage.

Furthermore, employing different analysis methods could enhance the depth of the investigation. While this thesis only analysed tissue damage from LapSim data and muscle co-activation from EMG, the think-aloud data were not analysed due to time constraints. Analysing this verbal data could reveal whether participants' self-awareness and self-regulation influenced muscle co-activation and tissue damage, providing valuable additional insights. Moreover, Lapsim data contains other performance parameters scuh as motion efficiency, by testing this further could possibly explained the causal relationship between muscle co-activation and tissue damage

In summary, future research should focus on refining the experimental design, exploring alternative tasks, integrating additional sensors, and analysing all available data, including think-aloud protocols, to gain a more thorough understanding of the dynamics between muscle co-activation and tissue damage.

4.1 Limitations and Recommendations

One limitation of this thesis is its exclusive focus on the execution phase of laparoscopy, neglecting the preoperative phase. Given that errors in laparoscopy fall within the domain of human factors, it is crucial to recognize that mistakes can also occur during preoperative planning. For instance, a surgeon might overlook critical details from the patient's medical history or select an inappropriate technique or strategy, potentially compromising patient safety. Incorporating preoperative error identification into the framework is essential for a comprehensive understanding of error management. Surgeons must meticulously review patient information, develop effective surgical plans, and anticipate potential complications. Including preoperative considerations in the framework would provide a more thorough examination of how early-stage decisions impact overall surgical performance and outcomes, leading to more effective error prevention strategies and enhanced patient safety.

Another limitation is the lack of insight into the cognitive processes of intermediates. The study primarily focuses on observable behaviours and muscle movements but does not address how intermediates mentally process and understand errors. Understanding these cognitive processes is vital for developing a comprehensive error management framework and improving training methodologies. Incorporating cognitive task analysis could address this gap by elucidating how intermediates conceptualise and approach errors, adapt their strategies, and how their mental models influence performance. This deeper understanding could facilitate the development of more targeted and effective training programs, ultimately enhancing error detection, recovery, and overall surgical proficiency.

Additionally, the thesis's focus on practices within the Netherlands may not account for cultural variations in laparoscopic training. For example, Noda et al. (2024) highlight that Japanese training methods, such as Laparoscopic Origami, do not incorporate performance parameters in the same manner as simulator-based training, which means performance metrics are not considered in their approach. Similarly, in Taiwan, training often involves group settings where peers observe and provide feedback, a factor not addressed by the current PIE framework. Investigating diverse training practices and feedback mechanisms from other countries could yield valuable insights into how the PIE model might be adapted. By integrating perspectives from various regions, the model could be refined to better address global variations in training and error management, thereby improving its comprehensiveness and effectiveness across different cultural contexts.

4.2 Conclusion

In this study, several limitations were identified. One major issue was the inability to capture the cognitive perspective of intermediates in the development of the PIE framework, preventing validation of the framework as originally designed. Additionally, the use of trend analysis limited the ability to establish a causal relationship between muscle co-activation and tissue damage during simulated laparoscopy, as merely observing muscle co-activation did not suffice for drawing conclusive causal inferences.

Despite these limitations, this thesis represents the first attempt to construct a framework for mapping cognitive processes during error identification in simulated laparoscopy and to explore the relationship between muscle co-activation and tissue damage using electromyography. It also provides insights into the associated learning curve.

Future research should focus on validating the PIE framework and further investigating the causal relationship between muscle co-activation and tissue damage in simulated laparoscopy to build upon these initial findings.

Reference

Abe, T., Raison, N., Shinohara, N., Khan, M. S., Ahmed, K., & Dasgupta, P. (2018). The effect of Visual-Spatial ability on the learning of Robot-Assisted surgical skills. *Journal of Surgical Education*, *75*(2), 458–464. https://doi.org/10.1016/j.jsurg.2017.08.017

Ahlberg, G., Enochsson, L., Gallagher, A. G., Hedman, L., Hogman, C., McClusky, D. A., Ramel, S., Smith, C. D., & Arvidsson, D. (2007). Proficiency-based virtual reality training significantly reduces the error rate for residents during their first 10 laparoscopic cholecystectomies. *The American Journal of Surgery*, *193*(6), 797–804. https://doi.org/10.1016/j.amjsurg.2006.06.050

Ateş, F., Temelli, Y., & Yucesoy, C. A. (2018). Effects of antagonistic and synergistic muscles' co-activation on mechanics of activated spastic semitendinosus in children with cerebral palsy. *Human Movement Science*, *57*, 103–110. https://doi.org/10.1016/j.humov.2017.11.011

Azungah, T. (2018). Qualitative research: deductive and inductive approaches to data analysis. *Qualitative Research Journal*, *18*(4), 383–400. https://doi.org/10.1108/qrj-d-18-00035

Begalle, R. L., DiStefano, L. J., Blackburn, T., & Padua, D. A. (2012). Quadriceps and hamstrings coactivation during common therapeutic exercises. *Journal of Athletic Training*, *47*(4), 396–405. https://doi.org/10.4085/1062-6050-47.4.01

Bjerrum, F., Maagaard, M., Sorensen, J. L., Larsen, C. R., Ringsted, C., Winkel, P., Ottesen, B., & Strandbygaard, J. (2015). Effect of instructor feedback on skills retention after laparoscopic simulator training: Follow-Up of a randomized trial. *Journal of Surgical Education*, *72*(1), 53–60. https://doi.org/10.1016/j.jsurg.2014.06.013

Bonrath, E. M., Gordon, L. E., & Grantcharov, T. P. (2015). Characterising 'near miss' events in complex laparoscopic surgery through video analysis. *BMJ Quality & Safety*, *24*(8), 516–521. https://doi.org/10.1136/bmjqs-2014-003816

Craig, C., Klein, M. I., Griswold, J., Gaitonde, K., McGill, T., & Halldorsson, A. (2012). Using cognitive task analysis to identify critical decisions in the laparoscopic environment. *Human Factors the Journal of the Human Factors and Ergonomics Society*, *54*(6), 1025–1039. https://doi.org/10.1177/0018720812448393

Cundy, T. P., Thangaraj, E., Rafii-Tari, H., Payne, C. J., Azzie, G., Sodergren, M. H., Yang, G., & Darzi, A. (2015). Force-Sensing Enhanced Simulation Environment (ForSense) for laparoscopic surgery training and assessment. *Surgery*, *157*(4), 723–731. https://doi.org/10.1016/j.surg.2014.10.015

Darainy, M., & Ostry, D. J. (2008). Muscle cocontraction following dynamics learning. *Experimental Brain Research*, *190*(2), 153–163. https://doi.org/10.1007/s00221-008-1457-y

Di Saverio, S. (2014). Emergency laparoscopy. *Journal of Trauma and Acute Care Surgery*, *77*(2), 338–350. https://doi.org/10.1097/ta.0000000000000288

Drăghici, L., Lițescu, M., Munteanu, R., Pătru, C., Gorgan, C. L., Mirică, R., & Drăghici, I. (2017). Errors and complications in laparoscopic surgery. *Journal of Clinical and Investigative Surgery*, *2*(1), 27–33. https://doi.org/10.25083/2559.5555.21.2733

Elessawy, M., Mabrouk, M., Heilmann, T., Weigel, M., Zidan, M., Abu-Sheasha, G., Farrokh, A., Bauerschlag, D., Maass, N., Ibrahim, M., & Kamel, D. (2021). Evaluation of laparoscopy virtual reality training on the improvement of trainees' surgical skills. *Medicina*, *57*(2), 130. https://doi.org/10.3390/medicina57020130

Franklin, D. W., Burdet, E., Osu, R., Kawato, M., & Milner, T. E. (2003). Functional significance of stiffness in adaptation of multijoint arm movements to stable and unstable dynamics. *Experimental Brain Research*, *151*(2), 145–157. https://doi.org/10.1007/s00221-003-1443-3

Gabitov, E., Lungu, O., Albouy, G., & Doyon, J. (2020). Movement errors during skilled motor performance engage distinct prediction error mechanisms. *Communications Biology*, *3*(1). https://doi.org/10.1038/s42003-020-01465-4

Gabrysz-Forget, F., Zahabi, S., Young, M., Nepomnayshy, D., & Nguyen, L. H. (2021). "It's a big part of being good surgeons": Surgical trainees' perceptions of error recovery in the operating room. *Journal of Surgical Education*, *78*(6), 2020–2029. https://doi.org/10.1016/j.jsurg.2021.03.015

Gallagher, A. G., & Satava, R. M. (2002). Virtual reality as a metric for the assessment of laparoscopic psychomotor skills. *Surgical Endoscopy*, *16*(12), 1746–1752. https://doi.org/10.1007/s00464-001-8215-6

Gallagher, A. G., Smith, D. C., Bowers, S. P., Seymour, N. E., Pearson, A., McNatt, S., Hananel, D., & Satava, R. M. (2003). Psychomotor skills assessment in practicing surgeons experienced in performing advanced laparoscopic procedures. *Journal of the American College of Surgeons*, *197*(3), 479–488. https://doi.org/10.1016/s1072-7515(03)00535-0

Gerges, F. J., Kanazi, G. E., & Jabbour-Khoury, S. I. (2006). Anesthesia for laparoscopy: a review. *Journal of Clinical Anesthesia*, *18*(1), 67–78. https://doi.org/10.1016/j.jclinane.2005.01.013

González, A., Barrios-Muriel, J., Romero-Sánchez, F., Salgado, & Alonso, F. (2020). Ergonomic assessment of a new hand tool design for laparoscopic surgery based on surgeons' muscular activity. *Applied Ergonomics*, *88*, 103161. https://doi.org/10.1016/j.apergo.2020.103161

Graneheim, U. H., & Lundman, B. (2004). Qualitative content analysis in nursing research: concepts, procedures and measures to achieve trustworthiness. *Nurse Education Today*, *24*(2), 105–112. https://doi.org/10.1016/j.nedt.2003.10.001

Grober ED, Bohnen JM. Defining medical error. Can J Surg. 2005 Feb;48(1):39-44. PMID: 15757035; PMCID: PMC3211566.

Groenier, M., Groenier, K. H., Miedema, H. a. T., & Broeders, I. a. M. J. (2015). Perceptual speed and psychomotor ability predict laparoscopic skill acquisition on a simulator. *Journal of Surgical Education*, *72*(6), 1224–1232. https://doi.org/10.1016/j.jsurg.2015.07.006

Hall C, Buckolz E, Fishburne GJ. Imagery and the acquisition of motor skills. Can J Sport Sci. 1992 Mar;17(1):19-27. PMID: 1322764

Henn, P., Gallagher, A. G., Nugent, E., Seymour, N. E., Haluck, R. S., Hseino, H., Traynor, O., & Neary, P. C. (2018). Visual spatial ability for surgical trainees: implications for learning endoscopic, laparoscopic surgery and other image-guided procedures. *Surgical Endoscopy*, *32*(8), 3634–3639. https://doi.org/10.1007/s00464-018-6094-3

Huang, H. J., Kram, R., & Ahmed, A. A. (2012). Reduction of Metabolic Cost during Motor Learning of Arm Reaching Dynamics. *Journal of Neuroscience*, *32*(6), 2182–2190. https://doi.org/10.1523/jneurosci.4003-11.2012

Humm, G. L., Peckham-Cooper, A., Chang, J., Fernandes, R., Gomez, N. F., Mohan, H., Nally, D., Thaventhiran, A. J., Zakeri, R., Gupte, A., Crosbie, J., Wood, C., Dawas, K., Stoyanov, D., & Lovat, L. B. (2023). Surgical experience and identification of errors in laparoscopic cholecystectomy. *British Journal of Surgery*, *110*(11), 1535–1542. https://doi.org/10.1093/bjs/znad256

Joice, P., Hanna, G. B., & Cuschieri, A. (1998). Errors enacted during endoscopic surgery—a human reliability analysis. *Applied Ergonomics*, *29*(6), 409–414. https://doi.org/10.1016/s0003-6870(98)00016-7

Jones, D. A., & Round, J. M. (1990). Skeletal muscle in health and disease: a textbook of muscle physiology. Manchester University Press.

Kohn, T., Corrigan, M., & Donaldson, S. (2000). To Err is Human: Building a Safer Health System. In *National Academies Press eBooks*. https://doi.org/10.17226/9728

Kontogiannis, T. (1999). User strategies in recovering from errors in man–machine systems. *Safety Science*, *32*(1), 49–68. https://doi.org/10.1016/s0925-7535(99)00010-7

Kopec, D., Kabir, M. H., Reinharth, D., Rothschild, O., & Castiglione, J. A. (2003). Human errors in medical practice: systematic classification and reduction with automated information systems. *Journal of Medical Systems*, *27*(4), 297–313. https://doi.org/10.1023/a:1023796918654

Latash, M. L. (2018). Muscle coactivation: definitions, mechanisms, and functions. *Journal of Neurophysiology*, *120*(1), 88–104. https://doi.org/10.1152/jn.00084.2018

Leape, L. L. (1994). Error in medicine. *JAMA*, *272*(23), 1851. https://doi.org/10.1001/jama.1994.03520230061039

Luursema, J., Verwey, W. B., & Burie, R. (2012). Visuospatial ability factors and performance variables in laparoscopic simulator training. *Learning and Individual Differences*, *22*(5), 632–638. https://doi.org/10.1016/j.lindif.2012.05.012

Mandrioli, M., Inaba, K., Piccinini, A., Biscardi, A., Sartelli, M., Agresta, F., Catena, F., Cirocchi, R., Jovine, E., Tugnoli, G., & Di Saverio, S. (2016). Advances in laparoscopy for acute care surgery and trauma. *World Journal of Gastroenterology*, *22*(2), 668. https://doi.org/10.3748/wjg.v22.i2.668

Matern, U., Kuttler, G., Giebmeyer, C., Waller, P., & Faist, M. (2004). Ergonomic aspects of five different types of laparoscopic instrument handles under dynamic conditions with respect to specific laparoscopic tasks: An electromyographic-based study. *Surgical Endoscopy*, *18*(8), 1231–1241. https://doi.org/10.1007/s00464-003-9162-1

Mayring, P. (2000). Qualitative content analysis. *Forum Qualitative Sozialforschung*, *1*(2). https://doi.org/10.17169/fqs-1.2.1089

Nezhat, F. (2008). Minimally invasive surgery in gynecologic oncology: Laparoscopy versus robotics. *Gynecologic Oncology*, *111*(2), S29–S32. https://doi.org/10.1016/j.ygyno.2008.07.025

Noda, Y., Hamamoto, S., Shiraki, T., Sakata, T., Tomiyama, N., Naiki, T., Matsumoto, D., Okada, T., Kubota, H., & Yasui, T. (2024). Original training for laparoscopic surgery by making an origami paper crane. *Cureus*. https://doi.org/10.7759/cureus.62098

Prasad, R., Manivannan, M., Manoharan, G., & Chandramohan, S. (2016). Objective assessment of laparoscopic force and psychomotor skills in a novel virtual Reality-Based haptic simulator. *Journal of Surgical Education*, *73*(5), 858–869. https://doi.org/10.1016/j.jsurg.2016.04.009

Quick, N. E., Gillette, J. C., Shapiro, R., Adrales, G. L., Gerlach, D., & Park, A. E. (2003). The effect of using laparoscopic instruments on muscle activation patterns during minimally invasive surgical training procedures. *Surgical Endoscopy*, *17*(3), 462–465. https://doi.org/10.1007/s00464-002-8530-6

Reason, J. (1990). *Human error*. https://doi.org/10.1017/cbo9781139062367

Ritter, E. M., Gardner, A. K., Dunkin, B. J., Schultz, L., Pryor, A. D., & Feldman, L. (2019). Video-based assessment for laparoscopic fundoplication: initial development of a robust tool for operative performance assessment. *Surgical Endoscopy*, *34*(7), 3176–3183. https://doi.org/10.1007/s00464-019-07089-y

Sancibrian, R., Redondo-Figuero, C., Gutierrez-Diez, M. C., Gonzalez-Sarabia, E., & Manuel-Palazuelos, J. C. (2020). Ergonomic evaluation and performance of a new handle for laparoscopic tools in surgery. *Applied Ergonomics*, *89*, 103210. https://doi.org/10.1016/j.apergo.2020.103210

Sandy, N. S., Da Cruz, J. a. S., Passerotti, C. C., Nguyen, H., Reis, S. T. D., Gouveia, E. M., Duarte, R. J., Bruschini, H., & Srougi, M. (2013). Can the learning of laparoscopic skills be quantified by the measurements of skill parameters performed in a virtual reality simulator? *International Braz J Urol*, *39*(3), 371–376. https://doi.org/10.1590/s1677-5538.ibju.2013.03.10

Satava, R. M. (2005). Identification and reduction of surgical error using simulation. *Minimally Invasive Therapy & Allied Technologies*, *14*(4–5), 257–261. https://doi.org/10.1080/13645700500274112

Soper, N. J., Brunt, L. M., & Kerbl, K. (1994). Laparoscopic General surgery. *New England Journal of Medicine*, *330*(6), 409–419. https://doi.org/10.1056/nejm199402103300608

Strandbygaard, J., Bjerrum, F., Maagaard, M., Winkel, P., Larsen, C. R., Ringsted, C., Gluud, C., Grantcharov, T., Ottesen, B., & Sorensen, J. L. (2013). Instructor feedback versus no instructor feedback on performance in a laparoscopic virtual reality simulator. *Annals of Surgery*, *257*(5), 839–844. https://doi.org/10.1097/sla.0b013e31827eee6e

Takagi, A., Maxwell, S., Melendez-Calderon, A., & Burdet, E. (2020). The dominant limb preferentially stabilizes posture in a bimanual task with physical coupling. *Journal of Neurophysiology*, *123*(6), 2154–2160. https://doi.org/10.1152/jn.00047.2020

Tang, B., Hanna, G. B., Bax, N. M. A., & Cuschieri, A. (2004). Analysis of technical surgical errors during initial experience of laparoscopic pyloromyotomy by a group of dutch pediatric surgeons. *Surgical Endoscopy*, *18*(12), 1716–1720. https://doi.org/10.1007/s00464-004-8100-1

Tang, B., Hanna, G., & Cuschieri, A. (2005). Analysis of errors enacted by surgical trainees during skills training courses. *Surgery*, *138*(1), 14–20. https://doi.org/10.1016/j.surg.2005.02.014

Thompson, A. K., Carruth, H., Haywood, R., Hill, N. J., Sarnacki, W. A., McCane, L. M., Wolpaw, J. R., & McFarland, D. J. (2018). Effects of sensorimotor rhythm modulation on the human flexor Carpi radialis H-Reflex. *Frontiers in Neuroscience*, *12*. https://doi.org/10.3389/fnins.2018.00505

Wottawa, C. R., Cohen, J. R., Fan, R. E., Bisley, J. W., Culjat, M. O., Grundfest, W. S., & Dutson, E. P. (2012). The role of tactile feedback in grip force during laparoscopic training tasks. *Surgical Endoscopy*, *27*(4), 1111–1118. https://doi.org/10.1007/s00464-012-2612-x

Zhu, F. F., Poolton, J. M., Wilson, M. R., Hu, Y., Maxwell, J. P., & Masters, R. S. W. (2011). Implicit motor learning promotes neural efficiency during laparoscopy. *Surgical Endoscopy*, *25*(9), 2950–2955. https://doi.org/10.1007/s00464-011-1647-8

Appendix A

Interview study materials

Interview Plan

Introduction

An interview will be conducted with laparoscopic experts in order to achieve the following goal:

- Determine different errors that occurred during the early learning phase of laparoscopy surgery from the perspective of experts on novices
- Common errors that experts (interviewees) have performed throughout their career
- Common and technical skills errors that experts (interviewees) witness (Performed by others) throughout their career
- Explanation of how these errors occur and reoccur
- The mental analysis of how experts recognise and determine such action is considered an error.
- Determine patterns of error identification of experts and novices (Based on the scope of the expert's observation)
- Identify how experts and novices recover common errors and determine the patterns of recovery
- Require the experts (interviewees) to classify the provided error from most common to least common. (consequences)

This interview should be able to provide us with insights and information about how experts detect errors and how they recognise such actions as errors. According to Bann et al. (2005), the ability to detect surgical errors is positively correlated with surgical expertise. In other words, novice surgeons are less likely to detect errors that occur during surgical procedures, as they are less experienced. This reflected that, by interviewing expert surgeons we can detect how surgeons detect errors, how they see such actions as errors, and how they think about what causes the error.

Based on the existing lietaure, we can identify 3 errors that are likely to occur in laparoscopy namely: excessive force, omission (incomplete suturing) & commission (wrong sequence) and Spatial/distance disorientation. However, most literature recommends that excessive force is recognised as the common error that is likely to occur in laparoscopy. These 3 errors will be given to the experts, where they will be asked to arrange the errors from most common to least.

<u>This interview will involve the following phase</u>
Phase 1: Construct interview questions
Phase 2: Conduct interviews

Phase 3: Code the interview (construct critical decision method + concept map)

<u>Phase 1:Construct the interview question</u>

This is a crucial step of the interview process, as I have to guarantee the question should be reflective enough that the interviewee can provide more insights on the errors that are likely to occur during a laparoscopy. Moreover, these questions should allow the interviewee to explain how the error came about and how they identified these actions as errors. Most importantly, these questions should not trigger the interviewee to "over share" their experiences and perspectives on errors occurrence during the laparoscopy.

The first step of this interview will be the recruitment of interviewees. As mentioned above, this interview aims to collect information on common errors that laparoscopy experts experience in their careers. However, the question is, what is considered an "expert" and how can a laparoscopy surgeon as an expert? Therefore it will be crucial to first define the term "experts" in terms of laparoscopy scope.

The interviewees for this interview should be experts in laparoscopy with extensive knowledge and experience in both laparoscopy and minimally invasive surgery. Each interviewee must have at least five years of experience in performing these procedures and be a certified surgeon practising in the Netherlands. Additionally, they should have experience in training novices in laparoscopy techniques, ensuring they can provide insights not only from a practitioner's perspective but also from an educator's standpoint.

The next step is to create the questions. Cognitive task analysis (CTA) and problem-centred interview (PCI) will be two great methods to take into account when constructing the questions.

PCI suggested that there should be follow-up questions, the questions should be open-ended questions, then general and specific questions as well as ad hoc questions. With general exploration, research can capture aspects and details that are not yet mentioned by the interviewee. Moreover, with specific exploration, we can gain more insights into the interviewee's opinions and thoughts. With ad hoc questions, we can look deeper into additional aspects or keywords that allow us to ensure the comparability of the interviews.

Moreover, this interview adapts to the CTA question design to capture the cognitive process of surgeons when handling and experiencing an error during laparoscopy

To better capture useful information, several codes were created

- **Situation assessment**: this refers to the situation where experts engage in a comprehensive evaluation of the current situation
- **Error detection**: This refers to situations where experts are able to detect errors that occur during the laparoscopy surgery. To be more precise, a surgeon encounters a stimulus that can cause negative consequences to the patient's safety, and such

stimulus is detected as an error. I argued that error detection will be followed by the following factors:

- **Error labeling** : occurs after the surgeon detects a certain stimulus as an error and identifies it as an error. In other words, the surgeons "termed" a certain action as an error as it has negative consequences for the patient's safety risk. For instance after a stimulus is presented, it triggers a specific response of the laparoscopy surgeons and interpretation will occur that will either result in intended action but wrong result or unintended action with wrong result.
- **Error: evaluation:** occurs after the surgeon identifies an error and understands the significance and potential impact of the error on the patient's safety and the success of the surgery. In other words, errors are now "mapped" in the knowledge of surgeons.

Figure 1 demonstrates an illustration of how these factors can be linked to each other.
Figure 1

- **Error recovery**: refers to the situation in which the surgeon successfully detects the error or errors during a laparoscopy surgery and applies strategies to recovery from the error (E,g "I need to avoid this by using less force, this mean I should have more control in my arm")
- **Cognitive process**: This refers to the cognitive process of how the surgeons come about the process of situation assessment, error detection (identification and recognition), and error recovery. (asking the how, why, what, where, whom)

Questions

Question	Purpose	Follow-up Question	Comment
Demographic information			
Could you please introduce yourself, and share with us your background in laparoscopy surgery, including how many years of experience you have in this field?	To collect basic demographic information for the participant section of the thesis.		Remember: 1. Thank the interviewee 2. Make sure to keep it short
Have you used a laparoscopy simulator in your career?	To collect the basic information on whether the interviewee has used a laparoscopy simulator before. This is also to avoid directly starting by asking the interview questions about error performances	How long have you been using the laparoscopy simulator?	Focus on the expert's opinions on using the simulator
What will be your opinions on involving laparoscopy simulators in training students? *	To collect the point of view on using a laparoscopy simulator training. This is also to avoid directly starting by asking the interview questions about error performances	Do you think it will have a positive/negative impact on student's skills in laparoscopy? *	

Error Identification Experience			
Based on your experience in laparoscopy, what type of errors are likely to occur in the early learning phase	To determine some common errors that are likely to occur in laparoscopy based on the early learning experience of the interviewee	Why do you think these errors are common in laparoscopy?	Take notes on the errors that are mentioned. Try to term the errors the interviewee mentioned and double-check with them.
Could you describe a specific error you have encountered a couple of times during a laparoscopy procedure at your early learning phase?	To capture the error that the experts personally experienced. This also helps to reflect on the experience that "pops up" into the mind of the interviewee. (First thoughts). This first pop-up of experience on error might be either it is the most remarkable experience or the errors that occur the most.	Could you further explain….? * You mentioned that…… however does this come about…? * At what point did you notice the error occurred?	This question may consume a significant portion of our interview time. Try to keep the interviewee on track and allow them to reflect more on their experience Term the error mentioned Double confirm the error with the participant
Under what criteria would a certain stimulus be considered an error at an early learning phase?	This helps trigger the interviewee to further explain how and why they think such an action/ is considered an error. This helps to detect the patterns of error identification.		Pay attention to information that is related to skills.
Has this error recurred? If so,	To further delve into the error		Use verbal and non-verbal cues to

what factors contributed to its recurrence? If not, what measures were taken to prevent its repetition?	experience of the interviewee To detect the recurrence of error why does occur again and why		the interviewee so they feel that they are being listened to.
Do you think, whether the level of skills has a role in the occurrence of this error?	To detect skills that are involved in laparoscopy error, this helps to detect the skills that are not mentioned by the existing paper.	What are the skills you think are related to this error? Do you think psychomotor skills could play a role? Do you think visuospatial skills could play a role?	Pay attention to the skills that were mentioned, this can help to detect other skills that are mentioned in the existing paper.
The existing papers have provided us with 3 most common errors that are likely to occur in the early learning phase of laparoscopy with is - Excessive force - Omission/ commission - Spatial/distance disorientation You also mentioned that XXX is an error that is likely to happen in early learning phase. Could you please arrange them from the most common to the least common	This is to range and rate the errors. We can then confirm whether the errors are indeed common and what are the common errors that are not mentioned in the existing papers.		Type the common errors out on the screen so the interviewee don't have to ask again as they might have been tired from the interviewee already.
Error performance of students (Intermediates/Novice)			

Have you trained or guided students on laparoscopy simulation training?	To see if the interviewee has experience in guiding/teaching students in using a laparoscopy simulator. If yes, this can show how students's skills relate to the use of	What are the level of students? Are they intermediates or novices?	Only proceed to the next question if the interviewee says yes!
Based on your experience what type of error are they likely to perform?	This is to gain the error performance from the third perspective view, especially from the view of experts. Also, students are less likely to notice the errors they made and less likely to detect it		Coin the term of the error they mention E.g.. "Students fail to control their hands " … so you mean students can perform less accurately when they fail to control their gestures?
What do you think is the cause of these types of errors?	To trigger some cognitive reasoning behind the error performance of students from an expert's point of view		
What are the recommendations you would give to these students for them to overcome the errors?	To determine possible error recovery strategies	What are the skills you think students should increase to prevent such errors? *	

Note: * These questions will be posed based on necessity and the availability of sufficient time to address them adequately

Phase 2: Conduct Interview

Before the interview
Send the interviewee an informed consent that includes the aim of the research, their rights of participation and contact details. Ensure the interviewee receives the meeting link. Moreover, a reminder email should be sent a day before the interview to remind the interviewee about their participation.

Before the interview begins, the interviewee should be provided with an outline of the interview and verbally explain their rights in this interview

Outline interview
Dear XXX

First of all, I am grateful for your participation in this interview. Before we begin with the interview I would like to provide an overview of the Master's thesis. This interview will be a part of my master's thesis named "Patterns of Identifying Errors in Laparoscopic Surgery: Constructing the PIE Framework". The objective of this thesis is to determine the patterns of error identification in the early learning phase of laparoscopy. I aimed to identify a framework that is able to clearly explain the links between laparoscopy simulator training, surgeon's skills and error identification.

Do you have any questions at this point?

This interview will be recorded, which means your answers will be recorded and transcribed for the purpose of data analysis for this thesis. The collected data will be stored confidentially and anonymously in the data that only I, the experimenter will have access to. However, the recorded video and transcribed interview will be removed 90 days after the thesis has ended. You are aware that, your participation is fully voluntary and you own all rights to withdraw your participation from this interview without providing any reason. All this information is stated in the informed consent that I sent you earlier, and it has my contact details and my supervisor's contact details on it.

Do you have any questions at this point?, if you have no further questions, I will begin the interview by starting the recording.

Ending
That's the last question for this interview, thank you very much for your time. Do you have any questions that you wish to discuss at this moment? If not I will proceed to end the recording for this interview.

Once again thank you for your participation.

Duration of the interview.

The interview should not be longer than 1.5 hours as it will bore the interviewee. Moreover, it might contain too much irrelevant information for coding.

After the interview

Email the interviewee again, address your gratitude to their participant and tell them that you will stay in contact so they can contact you anytime.

Phase 3: Code interview

Preparation for coding

1. Transcript of the recorded interview
2. Verify transcript accuracy by cross-checking with audio recording
3. Generate coder manual
4. Add code markers in the transcript
5. Annotate additional relevant information not addressed in the code with marker
6. Identify error identification patterns and visualisation

Interview Informed Consent

Consent Form for Error Identification Interview in Laparoscopy Simulation Training

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated [ ], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□
I consent voluntarily to be a participant in this interview and understand that I can refuse to answer questions and I can withdraw from the interview at any time, without having to give a reason.	□	□
I understand that taking part in this interview involves answering questions or experiences related to laparoscopy skills, laparoscopy simulator early learning phase, and psychomotor and visuospatial skills in laparoscopy.	□	□
Use of the information in the study		
I understand that the information I provide will be used for the analysis of error identification behaviours in laparoscopy. Moreover, this information will used in the Master Thesis of Sheng-En, Peng.	□	□
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	□	□
I agree that my answers to the interview questions can be quoted in research outputs.	□	□
I consent to be Audio and Video Recorded.	□	□

I understand that the recorded audio will be transcribed and stored confidentially and anonymously, which will not be shared beyond the study teams.

I understand that the recording of the interview will be removed 90 days after the fulfilment of the thesis.

I understand that I can freely communicate to the interviewer about the usage of my data and can not withdraw my participation after my answers have been used in the thesis.

Signatures

______________________ ______________________ ________

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_______Sheng-En,Peng______ ___________________ ________

Researcher name Signature Date

Study contact details for further information:

Sheng-En, Peng

s.peng@student.utwente.nl

Supervisors:

First Supervisor: Marleen Groenier

m.groenier@utwente.nl

Second supervisor: Russell Chan

r.w.chan@utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Natural Sciences and Engineering Sciences od the Faculty of Science and Technology at the University of Twente by ethicscommittee-nes@utwente.nl.

Coder manual

The aim of this coder manual is to create an outline and instruction on coding the collected interview data.

Instruction of coding

1. Stick to the code that have been created, do not create new codes while coding
2. Be objective when coding the interview
3. Do not change the transcript, even though it does align with the grammar rules, structure of the sentence does not matter.
4. Useful information that does not fits into the code, should be seen as extra information for other use.
5. Remove any data that contains personal information to avoid violating the confidential rule.
    a. Name, age, working location/position, working experience, student name etc

Steps to code the interview.

1. Use the coding layout (see appendix A)
2. Go through the transcribed interview, select the sentences that can be coded.
3. Paste the selected sentence into transcript column
4. Add the code
5. Add comments

Apply the code base on the instruction below:

Before coding, there are various aspect to keep in mind:

1. **Functionality**: Think about what the code does, it's purpose, and it's expected outcome
2. **Language**: This is not about the use of language, but the specific terms used to describe a scenario
3. **Example**: Focus on the example given, this can help to construct patterns of error identification

Code	Criteria to fulfil	Keywords
Situation Assessment	● Interviewee demonstrate a clear systematic process on assessing a situation when performing a laparoscopy (for both experts and novice). ● Demonstrate clear understanding of determining significant conditions of laparoscopy. ● Demonstrate process of collecting and analysing information to make judgement related to laparoscopic surgery.	● Evaluate (ing/ed)[1] ● Assess (ing/ed)/ assessment ● Examine (ing/ed) ● Judge (ing/ed) ● Review (ing/ed) ● Inspection ● Check ● Investigating ● Situation + XX[2] ● Observation ● Monitoring

	● Includes both summative (after task) and formative (during) evaluation.	● Determining ● Look
Error Detection	● Demonstrate clear indication on error during laparoscopy ● Demonstrate clear behaviour on encountering a stimulus during laparoscopy that is related to negative consequences to the patient outcome. ● Demonstrate certain cognitive process on linking the current situation with negative patient outcome ● Demonstrate clear behaviour on fully processing the stimulus and resulted in epiphany. ● This is about “oh there an error”	● Error ● Mistake ● Something is wrong ● Performed incorrectly ● Failure to success ● Recognise + XX_2 ● Notice + XX_2 ● Found ● Realise

Error Identification	● Demonstrate clear behaviour on recognising or/and recall a certain stimulus or/and action as error
	● Demonstrate clear behaviour on naming the detected error
	● Demonstrate clear behaviour o recalling from past experience in order to recognize certain action/ stimulus as error
	● Demonstrate clear behaviour on mentioning the possible negative consequence of patient outcome.
	● Clearly demonstrate that there is a stimulus that triggers something
	● Stimulus → response → interpretation → aligning with existing categories from experience
	● Clearly demonstrate behaviours on distinguishing between intended action leading to wrong result or unintended action leading to wrong result.
		● Visual inspection
		  ○ Anatomical recognition
		  ○ Tissues damage
		  ○ Bleeding
		  ○ Spatial disorientation
		● Haptic feedback
		  ○ Excessive force
		  ○ Resistance
		  ○ Instruments conflict
		● Does not goes as planned
		● Negative/ bad outcome
		● Hurt
		● Harm
		● Intended action
		● Planned action
		● Unintended action
		● Failure to achieve
		● Omission
		  ○ Miss a step
		  ○ miss a tool
		  ○ incomplete examination
		  ○ failure to follow surgical protocol
		● Commission
		  ○ Steps are performed incorrectly or inappropriately
		  ○ Messing up the order of surgery
		  ○ Use of wrong tool

		○ Mis-handling the tool ○ Misidentifying anatomical structure ○ Placing tools in incorrect angle ○ Improper suturing ○ Failure to identify the correct error
Error Evaluation	● Demonstrate clear behaviour linking the potential impact of the error on patent outcome ● Clearly demonstrate a cognitive recall to determine the performed error with related knowledge ● Linking to knowledge on ability, skills, recovery, strategies, reasoning, severity of error ● Able to identify error, and able to recognise that such error has occurred multiple times and are able to link recall such experience ● Recall experience resulted in the same error, demonstrating mental analysis on potential factors. ● Make connection of these factors from experience ● Demonstrate a mapping behaviour on resolving the error ● Demonstrate examination in actions and perform mental analysis to determine what are the possible factors leading to such error.	● In the past…. ● I think I need to….. ● Strategies ● Revision ● I have seen… ● I have saw multiple… ● I do think is because… ● Reasoning ● I think what leads to that is… ● Less + XX_2
Error Recovery	● Clear demonstrate application of strategies to reduce errors ● Clearly explain how does the strategies comes about ● Add support on why the mentioned strategies are workable, these support can be experience, self-inspection, recall information from book, feedback from simulator and feedback from supervisor. ● Clearly demonstrate the mental analysis of how the strategies are formulated ● Demonstrated confirmation of applying certain strategies at certain situation ● Mentioned the application of strategies successfully reduce the error *Here is not about	● Mistake handling ● I applied this…. And ….. ● It worked ● Revision ● Recovery ● Reconstruct the way I work ● Less error… ● Patient are less likely to be injure ● I recall a way too…. ● Reduce…. ● Limit… ● More control… ● Changes….. ● Revision on…..

	preventing the error, but is performed less by performance. ● Mentioned the application of strategies that are beneficial to patient outcome. ● Demonstrate revision on behaviours when performing laparoscopy	
Cognitive Analysis	● Verbalization of mental analysis when performing laparoscopy ● This is a general code to mark any cognition process that occurs during laparoscopy and is related to the other codes.	● I first… then… ● It appears to be…. ● I do think it is because.. ● Information given is able to construct a clear mental analysis mapping.

Note. 1. (ing/ed) refers to the futures and past tense of the keywords. 2. Combine with other words mentioned in the list. Definition of the codes can be found in interview plan (see above)

Appendix B

Experimental Study Materials

Figure B1

LapSim Simulator at TechMed Simulation Centre (TMSC) at the University of Twente, Netherlands.

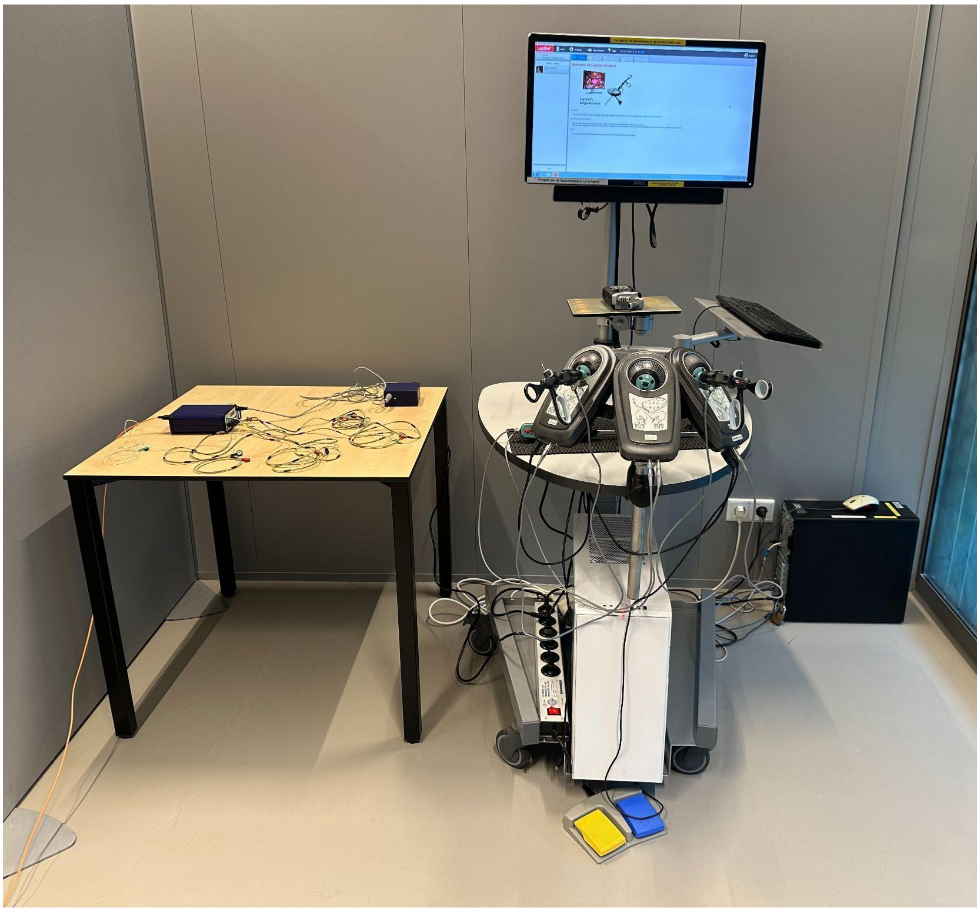


Figure B2

SimBalls with Laparoscopic Forceps Inserted

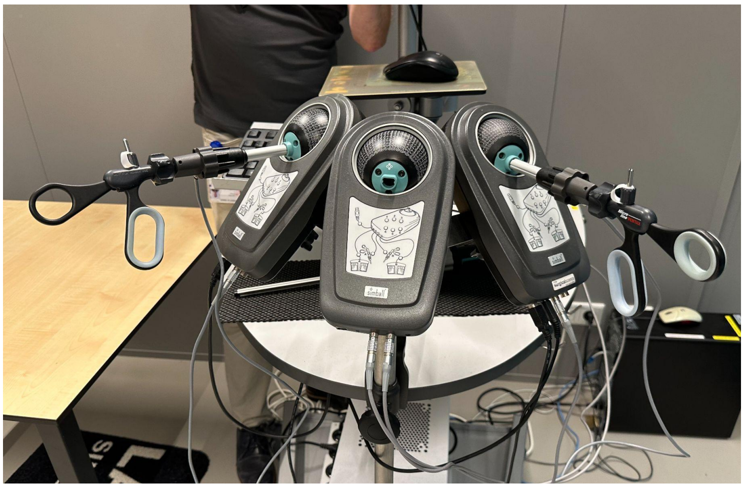
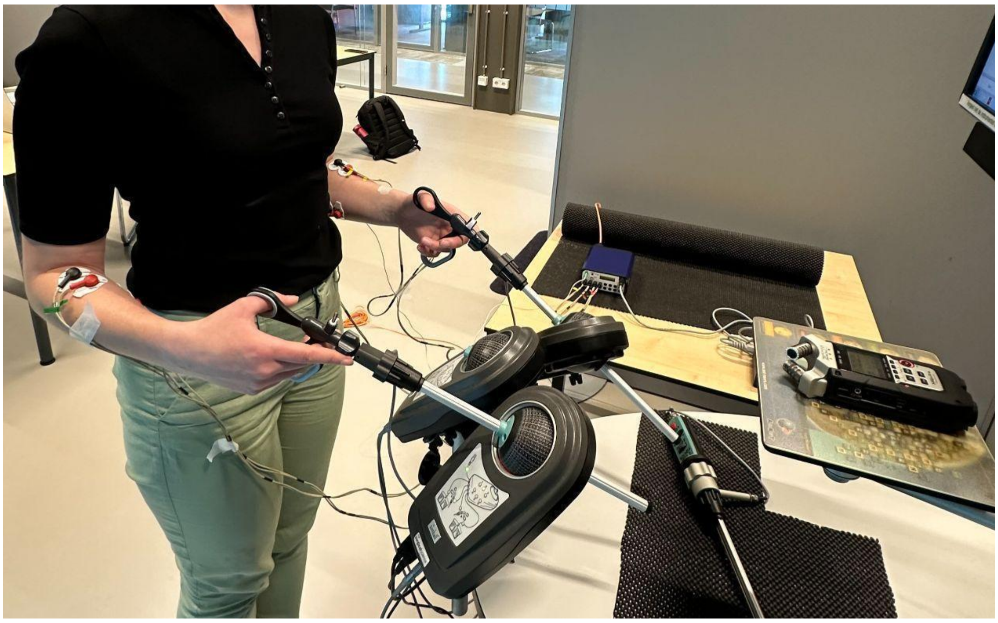


Figure B3

TSMi Porti 7 Connected to Flexor Carpi Radialis and Brachioradialis on Both Hands.



Note. The Zoom (H4N Pro) recorder is placed in front of the participant to record their verbalisation of cognitive process (Think-aloud)

Figure B4

TSMi Porti 7 Device

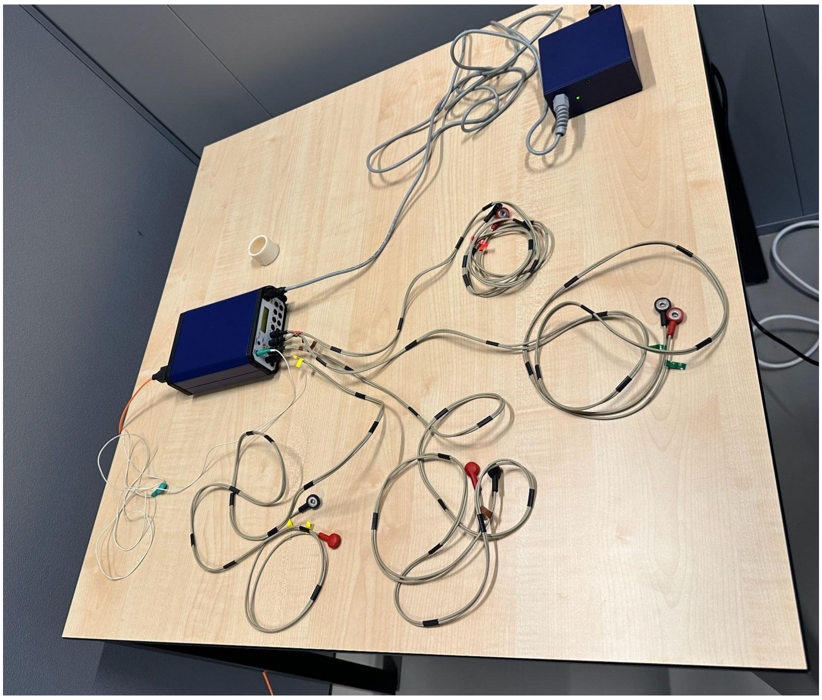


Figure B5

Electromyography Running on HP Pavilion 16-eg2980nd Laptop with the Polybench 5

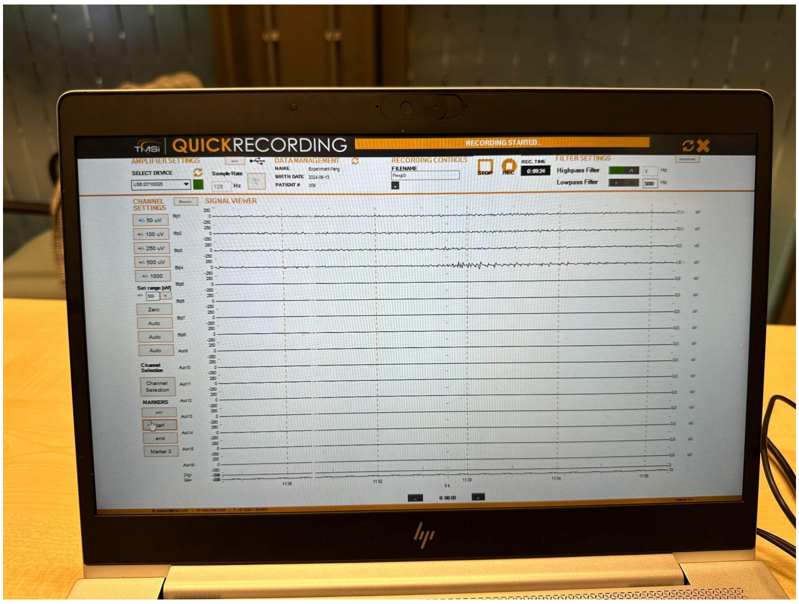


Figure B6

Visualisation of Experiment Setup

Appendix C

Experimental Manual

Set up

Lapsim Simulator

Steps to set up the simulator:

1. Turn on the power cord at the left
2. Turn on the computer tower
3. DO NOT TOUCH THE GREY COMPUTER TOWER AT THE RIGHT
4. Lock in the computer with Admin
5. Lock into the Lapsim system based on the participant account for easy data export
6. Place the forceps into the simulator, DO NOT TOUCH THE BALL
7. Ensure there is space for EMG and Recorder
8. Use the following username and password for each participant

login	ww
xx	xx

Participants:

login	ww
xx	xx
xx	xx
xx	xx
xx	xx
xx	xx
xx	xx
xx	xx
xx	xx
xx	xx
xx	xx

TSMi EMG

Steps to set up:

1. Plug in the power cords, connect all wires
2. Set up the TMSI data manager, use the same file

3. Open poly bench
4. Attach the wires to the correct electrode pod. *Make sure to follow the table below so when analysing the data they are the same.
   a.

Muscle	Electric channel	Code
Left flexor carpi ulnaris	B1	L11
Left brachioradialis	B2	L7
Right flexor carpi ulnaris	B3	R11
Righ brachioradialis	B4	R7

5. Paste the electrode patches to the muscle with adhesive electrodes.
6. Enter participant number
7. Enter the following:
   a. Sampling hz → 128 HZ
   b. Add markers → start, end
   c. Turn on the high pass filter
   d. Press record before the participant starts
   e. Keep an eye on the participants and add markers when they start the task and when they complete it.

Recorder

Steps to set up

1. Slide the buttons on the left side of the recorder.
2. Press record
3. Press play.
4. Plays the recorder near the participants
5. Remember to charge the recorder

Procedure Instruction

To ensure that participants can directly perform the experiment as soon as they arrive, it is crucial to arrive at least 45 minutes before the experiment to set everything up and have sufficient time to fix any pop-up issues.

After the participants have been greeted warmly, they will given an overview of the experiment and presented with printed information consent and a copy that they can take with them.

All participants will receive verbal introduction as follows:

Dear Participants,
First of all, huge thanks for your participation in this research. Before we begin with the experiment with the simulator, I would first like to provide you with an overview of the research. The purpose of this research is to investigate different error identification patterns when engaging in laparoscopy surgery. However, it is crucial to know that the research will not access your skills and abilities in laparoscopy surgery, in fact, your involvement will help us to better revise the current laparoscopy system into something more user-friendly.

The experiment takes about 2 hours to complete. You will be asked to complete certain tasks from the simulator. While performing these tasks, you will be connected to the EMG (point to the EMG.), I will apply these electrode patches on your arms (show the patches), then you will be connected to the electrode wires. Please note that the wires are very fragile, please be gentle. But we have tested a couple of times, this will not affect your performance in the simulator. As removing the electrode will cause inaccuracy in the data collection, I strongly recommend you to use the bathroom now, before we start with the experiment.

Throughout the experiment, we would like to ask you use the think-aloud method. It means that you verbalise every step in your mind, kinds of reflection your cognitive process. For example, when you trying out a new recipe you go: It looks i need sugar, hmm where is the sugar? Oh found it, now i will have to add it in, how much should I add? Oh okay about 2 tsps, oops I think I added too much, I guess coping it out will help. You can do it in English or Dutch based on your preferences. Please verbalise when you start the task, for instance, when you begin with task 1 you will “begin task 1, or start task 1” whatever is suitable for you as long as you mention the task number and you are starting it. Please do the same for the ending of the task. So we can keep track of the recording.

You are welcome to take breaks during the experiment, as you will be standing, please let me know I will assist you on that. However we can have any food or beverage in this room, so if you need water please let me know I will arrange something for you. Do you have any question at this point?

If not this is an inform consent, you may read and let me know if you have any questions and a copy of this will be provided.

I will proceed to assist in setting up the experiment.

Experiment set up for participants

1. Request participants to come with short shelves
2. Request participants to remove any jewellery on their hand or arm
3. **To label muscle group 11 as participants to create a fist and push that fist against the bottom of the table → clean with alcohol patches → stick on patches.**
4. **To label muscle group 7 ask participants to grasp into a fist real hard → clean with alcohol patches → electrodes patches**
5. Head to the simulator
6. Connect the electrodes, red should be closer to the wrist
7. Make sure the emg is running correctly.
8. Set up the simulator tasks.

Data naming

All files should be names with the following order:
Participants no._types of data_version

Data storing

All Data should be stored confidentially and anonymously that can only be accessed by the experimenter and the supervisors. All data is stored in one drive that is protected by the University of Twente. Moreover, to ensure data loss, I have a copy of the data in my personal pen drive that is stored securely.

Appendix D

Task and Time Tracker

Participant number: __________ Date: _____________________

EMG file: ____________________ Recording file: _______________

Scenario No.	Task	Scenario No.	Task
1		16	
2		17	
3		18	
4		19	
5		20	
6		21	

7		22	
8		23	
9		24	
10		25	
11		26	
12		27	
13		28	

14		29	
15		30	

Appendix E

R Script

R code