UiT
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Web-Based Surgical Telementoring

Service design and evaluation of the key features

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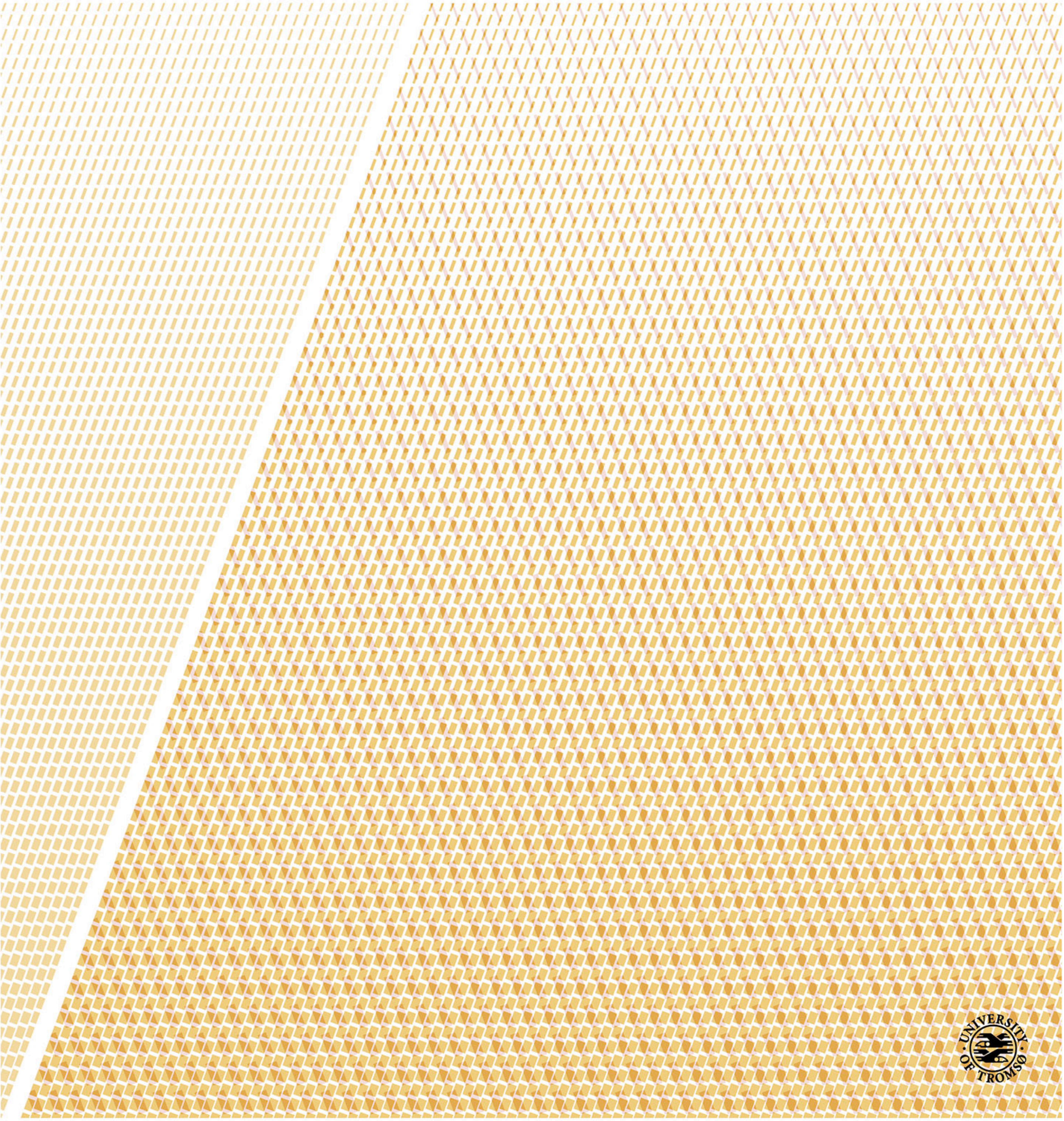

This dissertation is inspired by and dedicated to the fascinating nature of northern Norway

Definitions

Telemedicine: “The practice of medicine and/or teaching of the medical art, without direct physical physician-patient or physician-student interaction, via an interactive audio-video communication system employing tele-electronic devices” [1].

Telementoring: “A real-time and live interactive monitoring (evaluation) of technique(s) or procedure(s) of an applicant seeking privileges, or a surgeon seeking to certify or document his competence in a specific technique or procedure(s)” [1].

Teleconferencing (video conferencing): “A real-time and live interactive program in which one set of participants are at one or more locations and the other set of participants are at another location. The teleconference allows for interaction, including audio and/or video, and possibly other modalities, between at least two sites” [1].

Teleproctor (mentor): “An expert surgeon (…) who undertakes to impart his/her clinical knowledge and skills in a defined setting to a student. (…) The teleproctor, by definition, does not have the ability to physically intervene on-site in the primary activity without the telecommunications interface” [1].

Telestration: A technique enabling the drawing of freehand commands over still image or video. In this research project, telestration is explored as an extra modality for mentor–mentee communication [2].

Minimally invasive (laparoscopic) surgery: “Surgery done with only a small incision or no incision at all, such as through a cannula with a laparoscope or endoscope” [3].

Abbreviations

VC: Video conferencing

WebRTC: Web real-time communication

RCT: Randomized controlled trial

UNN: University Hospital of North Norway

UiT: University of Tromsø – The Arctic University of Norway

NST: Norwegian Centre for Integrated Care and Telemedicine

ICT: Information communication technologies

NHN: Norwegian Health Network[1] (*Norsk helsenett*)

API: Application programming interface

OSI model: Open systems interconnection model

P2P: Peer-to-peer

SSL/TLS: Secure sockets layer / Transport layer security

HTTP(S): (Secure) Hypertext transfer protocol

DTLS/SRTP: Datagram transport layer security / Secure real-time transport protocol

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[1] https://www.nhn.no

Preface

The work reported in this thesis summarizes personal and professional development, trying to bridge two, in some cases very distant, domains: computer science and medicine. As for someone with a computer science background, research and application in medical settings was both a challenging and an exciting experience. The widespread gap between the disciplines was eye opening, making me understand the complexity of the interdisciplinary research within medical informatics.

The different research initiates in engineering and medicine pointed out unexplored angles in the development and application of VC systems in healthcare. Having the potential of surgical telementoring in mind, I looked into state-of-the-art systems and their limited integration into clinical practices. My engineering background helped me to identify some weaknesses of the highly specific research infrastructure and propose a generalized solution for developing and integrating VC-based systems—surgical telementoring in particular. I took advantage of the technological novelties to implement the conceptual ideas and employed the system in non-clinical studies.

Research activities brought together technological and clinical expertise to increase the use of telementoring. In contrast to many earlier research initiatives, mostly dominated by clinicians, this project looked into the components of the telementoring process to provide generalized conclusions instead of extensive trials in various clinical scenarios. It mapped a vague technical definition of telementoring to the international regulatory frameworks and emphasized the patient perspective in safety-critical scenarios.

Regardless of the collaboration with the Norwegian healthcare system, the project aimed to produce knowledge of high international importance. The ideas of inter-organizational cross-border collaboration were one of the moving forces, distinguishing the project from earlier initiatives. The complexity of the organizational matters, lacking legal documents on responsibility-sharing in the collaboration of mentors and mentees, and implementation challenges prevented the development of a high-scale mentoring network in the scope of this PhD thesis. However, I hope the work contained herein builds solid fundamentals for further research initiatives.

Summary

This thesis provides a detailed outlook on research in telementoring, identifying the fundamental limitations hindering its smooth integration into clinical practice. The findings are based on literature reviews and user involvement, minimizing the gap between research and actual use of the system. To address the identified shortcomings, a service-oriented approach to clinical VC systems was proposed. The implementation was validated through non-clinical experiments regarding the published quality indicators and assessing the readiness of the web technologies supporting the selected workflow.

The developed theoretical models visualized the relations between the clinical and educational outcomes of telementoring, defining the methodology for the PhD project. The proposed measurement procedures were followed throughout the studies evaluating the usability of telementoring-capable hardware to ensure that sufficient qualities of mentoring are maintained regardless of the employed infrastructure. The findings demonstrated the feasibility of end-user hardware-agnostic mentoring and provided insights on the influence of the input method on the mentoring process.

A highly rated telestrator capacity was investigated to quantify its impact on the mentoring process. The potential for enhancing collaboration between mentors and mentees was studied, and unexpected findings were collected. Minor quantitative improvements and side effects encourage further exploration of collaboration techniques for surgical supervision.

This thesis provides in-depth knowledge on the development and deployment of surgical telementoring systems following international regulations and keeping patient safety concerns a top priority. This project aimed to unite the fragmented research on surgical telementoring, bridging technological and clinical perspectives. It brought the best computer science practices into a field mostly dominated by clinical expertise. It stressed the importance of a reusable large-scale infrastructure, delivering sound and comparable clinical research; this is in contrast to the current body of knowledge, which is overwhelmed by highly restrictive and underpowered studies.

Research contributions achieved in the scope of this PhD thesis are aligned with national regulations for introducing a safety-critical system into clinical settings. The findings contribute to approving the telementoring service as a medical device to proceed with clinical evaluation.

Acknowledgements

During the period of my PhD project, I was blessed to meet and work with many brilliant people who left a mark on my career as a researcher. Unfortunately, I am not able to mention and thank each of them individually for their contributions to the success of this challenging project.

First of all, I would like to thank my supervisor, Prof. Johan Gustav Bellika. His endless support and engagement in the project activities made the last few years an invaluable experience. His critical insight and advice brightened even the darkest days of the project and encouraged me to move forward. Besides research, Gustav was my guide in understanding Norwegian culture and even encouraged me to begin snowboarding. Dear Gustav, I am eternally grateful to you and your lovely family for your help and support on my quest for a PhD.

I would like to thank my co-supervisor, Prof. Gunnar Hartvigsen, for his effort to make this project succeed. His scientific expertise combined with the social initiatives to keep the researchers together introduced me to academia in Tromsø. Thank you, Gunnar, for your precious contributions.

The project would not be possible without the support from the Gastroenterological Surgery Department at UNN. I would like to thank the surgeons for their patience while participating in a trial. I especially thank Prof. Rolv-Ole Lindsetmo and Dr. Kim Mortensen for their help in designing and organizing the trials.

A big thanks to Stig Pedersen and Marianne Holmegård for their help in organizing the experiment at the Skill Simulation Center (FOSS) at UNN, the telemedicine and ehealth students at UiT, and Per Hasvold at the Norwegian Centre for Integrated Care and Telemedicine (NST) for sacrificing their precious time to participate in the trial. Your help is greatly appreciated.

During this PhD project, I was given the chance to supervise a master's student Timotheus Kampik. I can proudly say that supervision was definitely a two-way learning process for both of us. Thank you, Timotheus, for helping with the system development and sharing your experience with me.

I cannot stress my gratitude enough to the NST for hosting the project and supporting my six-month research stay at North Carolina State University, NC, USA. Being surrounded by such multidisciplinary expertise widened my computer science-focused perspective and

highlighted new angles in current and future research projects. Thank you to everyone for being there for me.

I am grateful to senior researcher Knut Magne Augestad, who was one of the initiators of the project and contributed significantly to starting the project. Prof. Hiten Patel was kind enough to share his hands-on experience with telementoring and introduce me to the processes in the operating room while observing live surgeries. Thank you, Knut and Hiten, for your contributions.

I am very grateful to all of the coauthors of the research papers. Your input and effort to disseminate knowledge resulted in nine publications, which are included in this thesis. Thank you very much.

I want to thank the regional healthcare authorities, Helse Nord RHF, for funding my research and contributing to my education as a researcher.

Another big thank you goes to my family, who has always supported me and encouraged me to reach for my goals. I cannot thank my mother enough for her infective optimism and endless care (especially over distance) during the intense periods of this project.

And last but not least, I want to thank my girlfriend, Ewelina, for putting up with me in the time-consuming process of earning a PhD. Let this milestone begin a new period in our lives.

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1. Introduction

1.1 Background

Every one of us is witnessing the rapid technological progress shaping our daily lives in a form never seen before. Ubiquitous mobile technologies, increasing wireless data transmission bandwidth, and growing computational power are constantly present in the form of mobile devices that are always close by. These introduce a new medium for transforming healthcare services, moving them one step closer to users [4]. This creates a fertile ground for the rapid development of telemedicine, moving medical practices to cyberspace and interactive audio video communication channels, minimizing the need for a physical clinician–patient meeting [1]. Increasing the availability and accessibility of healthcare services and minimizing travelling costs and time consumption are only a few of the potential advantages these technologies bring. However, the ongoing shift has a down side. Increasing dependency on technology and the ever-growing number of systems in hospitals raises integration challenges on the local, national, and international level. More focus is being directed towards the use of certain technologies instead of clinical matters [5].

Population analyses predict a growing demand for healthcare services, especially in the surgical workforce. The limited supply of surgical personnel highlights the growing threat of delayed treatment due to lack of resources [6], [7]. Such a scenario may happen even sooner than expected—a shortage of specialized surgeons in the USA is predicted for the year 2020 [8]. Given the timeframe and costs of training a surgeon, prolonged waiting lists in surgical departments are inevitable. This calls for immediate changes in surgical education as well as the increased efficiency of surgical departments within hospitals.

Telementoring has been described as a "surgical tool of the future," with its application ranging from providing guidance during a live surgery to remote training [9]. The outcomes of the approach are comparable to the standard practice of handling such cases—on-site supervision [10]. Numerous attempts of telementoring in clinical settings have been made over the years; however, a comprehensive knowledge base providing systematic proof is still lacking, as are the corresponding regulations, standardization, and systematic large-scale implementations in clinical settings.

This thesis analyzes the aforementioned problems mostly from computer science and sociocultural perspectives. It focuses on studying the telementoring process, implementation strategies, and usability properties to provide a strong foundation for clinically directed research.

1.2 Motivation

Geographical and financial constraints call for improving the collaboration of medical experts to enable the smooth exchange of knowledge, faster training of novices, and increased quality and efficiency of surgical operations. VC is a common approach for minimizing the consumption of expensive resources to provide the best available treatment for the patient using virtual communication channels. VC in the field of surgery is not a novel technology; however, its actual application and potential to improve patient outcomes has been underexplored [11].

To date, VC is associated with high installation and maintenance costs as well as reliability problems, resulting in user's resistance to employ it in clinical workflows [5], [12]. The complications are mostly evident in cases when the endpoints of the link are not known in advance (for instance, contacting a remote senior surgeon in the case of an emergency). Due to the lack of control of the underlying infrastructure between the mentor and mentee, a reliable, secure, and safe VC link cannot be preconfigured and tested in advance. It has to be available "on the fly" and use the computational device available on the mentor's side. Due to these technological limitations, such workflows have not previously been analyzed in the literature.

The described scenario is common in surgery when a senior expert who is not available on site needs to be contacted to provide his or her opinion on the case and guide the staff in the operating room through the procedure. Numerous experiments prove the benefits of telementoring in clinical and educational settings [13], [14]; however, all of the previous research is based on well-defined endpoints of the mentoring link: both actors are in controlled locations connected to previously tested networks and using preconfigured hardware. Increasing life dynamics, unplanned changes in schedules, and emergency cases call for an upgrade in the infrastructure for supporting telementoring on the device of the mentor's choice without preconfigurations.

1.3 Research questions

The research is focused on restructuring telementoring from a research technique mostly used in simplified settings to a daily tool in surgical practice. The impact of the novel approach of providing telementoring as a service and employing ubiquitous mobile devices as hardware to participate in a session was studied. In addition, a detailed investigation into the use of telestration in surgical telementoring scenarios is used to identify the benefits and quantitative properties of the feature.

The research questions are summarized as follows:

Q1: *Do modern web technologies provide a sufficient foundation for developing a surgical telementoring service?*

Explanation: Web technology support of VC has been limited to browser plugins that have to be installed and maintained on the client devices. Recent development has overcome this bottleneck, offering plugin-less alternatives that improve the usability and availability of VC services. However, are the technologies mature enough to be used in the healthcare context? Can they become the foundation of VC-based interactions within healthcare?

Q2: *How is mentor response to a mentoring request time influenced by the properties of mentoring hardware?*

Explanation: To date, surgical telementoring is associated with stationary hardware that often requires designated mentoring posts. Ubiquitous telementoring service frees mentors from such a stationary infrastructure, enabling remote supervision from mobile devices of their choice (e.g., tablet, computer, smartphone). It is assumed that performing mentoring on mobile devices instead of a stationary device will increase the availability of mentors and shorten the response time.

Q3: *Does performing mentoring on different hardware result in comparable outcomes?*

Explanation: Properties of the device the mentor is using to guide the mentee through the operation influence the mentoring process. Screen size and input type (mouse/touchscreen) affect the mentor's ability, speed, and accuracy in perceiving the video from the operating room and providing verbal and graphical responses. Do the aforementioned differences create significant threats to the mentoring process while mentors change mentoring hardware? What devices should be used for telementoring?

Q4: *Does the use of telestration while telementoring increase the speed and accuracy of surgical tasks (clinical outcomes)?*

Explanation: Supplementing VC-based mentoring with an annotation feature enables graphical guidance of the mentee in addition to verbal instructions. Decreased duration of surgical tasks and improved accuracy of mentoring is expected due to the ability to mark certain locations on top of live video instead of describing them verbally.

Q5: *Does the use of telestration while telementoring improve surgical education?*

Explanation: The graphical dimension in surgical telementoring introduces an additional perspective to the established verbal guidance. In addition to unambiguous localization, it changes the perception of the mentor's commands. What impact does it actually have on surgical education?

Q6: *Does the use of telestration increase the quality of telementoring?*

Explanation: The graphical guidance modality in addition to verbal supervision influences the interaction between the mentor and mentee. Do these changes improve the mentoring process?

1.4 Research approach

The research project began by analyzing published studies on telementoring and looking for the weaknesses of the presented approaches (summarized in section 2.2). Major inconsistencies in reporting revealed the lacking global vision of the use of and experimentation with telementoring and its integration into clinical workflows. In addition, minor (or non-existent) concerns of complying with the legal regulations were identified. This input was used to design and develop a novel approach to telementoring—a hardware-agnostic service. Service-based orientation enabled the standardization of VC interactions, providing a customizable gateway for developing communication systems in the healthcare network.

The proposed ideas were validated via technical testing and comparison to the accepted latency threshold [15]. RCTs looked into the usability options of telementoring hardware, measured and quantified the benefits of telestration while mentoring. The research approach is summarized in Figure 1.

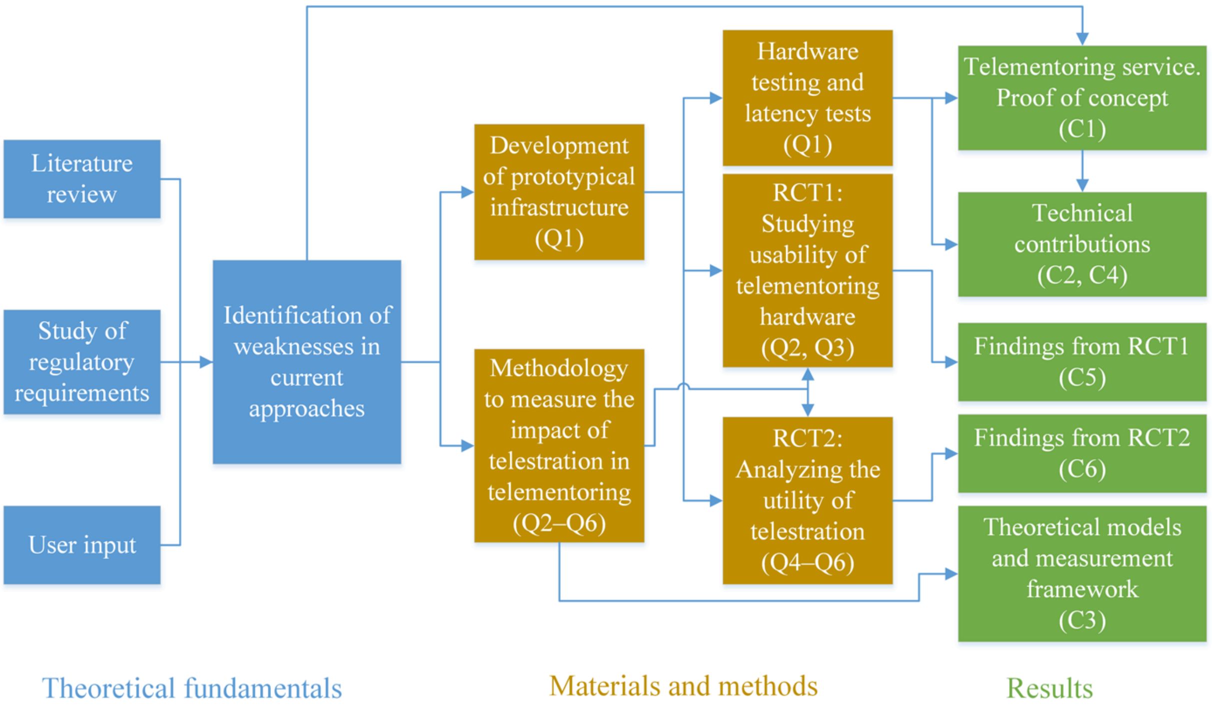

Figure 1. Research approach and organization (Q = research questions, C = research contributions).

1.5 Methods

This thesis combined a set of standardized and unstandardized research methods. A systematic literature review (section 2.1) identified a gap in the published research and highlighted the relations to the available knowledge base. A comparative study (section 3.1) helped in selecting the technological fundamentals for the novel implementation. Technical properties of the setup were evaluated by comparing the latency of the system to the published thresholds (section 4.2). Two RCTs in non-clinical settings assessed the usability properties of telementoring-capable devices (section 4.3) and the utility of telestration functionality (section 4.4). Methods for every mentioned activity are defined in detail in the corresponding sections below.

1.6 Limitations

The major limitation of this thesis is the absence of a clinical evaluation of the proposed system. Changes in the regulatory documents have introduced additional safety measures, preventing the planned progress into the operating room settings [16]. My study was continued in test environments, tailored with the help of clinical experts to become representative. Surgeons and students participated in the trials to bring the findings closer to the actual case. A relatively low number of participants, all of whom came from institutions with over the average focus on telemedical solutions, may have resulted in more optimistic evaluations.

1.7 Significance of the study

Computer science

This thesis demonstrates that novel web technologies are a sufficient fundament for developing clinical VC services. A novel concept of telementoring service in the healthcare network is proposed, implemented, and validated in non-clinical trials. Additional studies questioned the usability of telementoring hardware with regards to the behavioral changes of mentors to ensure that mentoring quality remains constant regardless of input technology, representativity of different screen sizes, and mobility perspective. The utility of a highly rated graphical annotation feature in the context of real-time supervision and education of the surgeons was researched—it was concluded that it had a surprisingly low impact (section 4.4).

Healthcare

This study identified the weaknesses of previous research attempts in telementoring. A novel system was proposed, minimizing the drawbacks of the analyzed solutions and standardizing the interventions. In addition to the technical contributions, RCTs and performed studies gave an insight into the factors influencing the quality of the telementoring process, their dependencies, and their quantification. The studies contributed to making telementoring an acknowledged part of clinical practice while simplifying its deployment and increasing the availability and flexibility of the service.

Patients

This project mapped the requirements from the international legal documents to the use of telementoring systems in clinical settings. Patient safety questions were emphasized while analyzing the published research and proposing the solutions for further development. Publications, produced in the scope of the project, are the only available criticism of the clinical research, ignoring the patient safety perspective and international regulations while experimenting with telementoring.

1.8 Claimed research contributions

Being on the frontier of developing novel clinical VC services is both exciting and challenging. Timing is essential in determining the importance of the research contributions. It is crucial to note that in the beginning of the PhD project, no initiatives of web-based VC in surgical telementoring were identified (see section 2.2). The multidisciplinary research is responsible for the following contributions:

C1: *A concept of "telementoring as a service" in healthcare networks*

The analysis of the earlier attempts to develop remote guidance systems for surgery identified major usability and availability problems ignored by clinical personnel (section 2.2). A novel idea of an infrastructure-agnostic telementoring service was proposed and validated in non-clinical studies.

Anchoring to the research questions: Q1

Relevant papers: P2, P4, P8, P9

C2: *A generic architecture for developing clinical VC services*

An analysis of telementoring applications (section 2.2) and additional cases of applying VC in healthcare revealed inconsistencies in design, development, and reporting of the achieved results. The lack of a standardized medium meeting the common set of requirements for clinical VC services was identified. A generic architecture to support large-scale implementation for a VC-based collaboration platform within healthcare was proposed.

Anchoring to the research questions: Q1

Relevant papers: P4, P8

C3: *Theoretical models for assessing the utility of telestration*

The relationships between clinical and educational outcomes of telementoring are summarized in the theoretical models. Together with the defined measurement procedures, they provide a comprehensive framework for assessing the changes in the mentoring process due to the use of live video annotation.

Anchoring to the research questions: Q4, Q5, Q6

Relevant papers: P1

C4: *Telementoring service prototype*

A functioning telementoring service prototype was developed reusing the generic VC service prototype and validated in non-clinical trials. It evaluates the feasibility of WebRTC as a technological foundation for developing a surgical telementoring service. Together with the results from the trials, it serves as an input for proceeding to the clinical studies.

Anchoring to the research questions: Q1, Q2, Q3

Relevant papers: P2, P4, P6, P7, P8, P9

C5: *Evaluation of usability characteristics of telementoring hardware*

Increased efficiency due to the use of telementoring service on mobile devices was proven; furthermore, there were no significant differences in the mentoring outcomes regardless of the properties of the mentoring hardware.

Anchoring to the research questions: Q2, Q3

Relevant papers: P2, P5

C6: *Assessment of the utility of telestration in surgical telementoring*

Telestration decreases the duration of mentoring episodes during the procedure; however, telestration has a minor influence on the accuracy of clinical task completion in comparison to verbal supervision. Graphical annotations deter the efficiency of education and introduce safety-critical implications.

Anchoring to the research questions: Q4, Q5, Q6

Relevant papers: P3, P5, P6

1.9 Primary included publications

P1: A. Budrionis, K. M. Augestad, H. R. Patel, and J. G. Bellika, "An Evaluation Framework for Defining the Contributions of Telestration in Surgical Telementoring," Interactive Journal of Medical Research, vol. 2, no. 2, p. e14, Jul. 2013.

Description of the paper: A systematic literature review targeting the evaluation of telestration in telementoring identified a gap in the current research. A theoretical framework and measurement procedures were proposed for studying and reporting live video annotation in surgical telementoring sessions. The relations between the concepts defined the potential effects and mapped them to the clinical and education benefits of telementoring.

The paper defined the overall methodology for the PhD project and future research within telementoring.

Author contributions: I was the key person in planning the paper, performing the review, and writing the manuscript. J. G. Bellika helped with structuring the review process and designing the theoretical framework, while H. R. Patel and K. M. Augestad helped in identifying the meaningful relationships in the models and suggesting measures for clinical concepts.

P2: A. Budrionis, G. Hartvigsen, R. O. Lindsetmo and J. G. Bellika, “What device should be used for telementoring? Randomized controlled trial,” International Journal of Medical Informatics, 2015, doi:10.1016/j.ijmedinf.2015.05.004 [in press]

Description of the paper: The proposed and implemented telementoring service freed the mentors from using preconfigured hardware designated for mentoring. The ability to provide mentoring from the device of mentor’s choice raised the question of sustaining the qualities of the process while perceiving and interpreting the transmitted video on various hardware. A crossover RCT asked the surgeons to participate in an imitated mentoring session on three types of devices in a random order. The study revealed minor significant differences in the behavioral patterns of the mentors—only response time to a mentoring request and total number of mentor–mentee interactions were device-dependent.

The trial concluded the comparable outcomes of telementoring sessions regardless of the employed devices. However, due to the safety-critical use case, the minor reported differences have to be kept in mind while designing graphical user interfaces for platform-agnostic telementoring services.

Author contributions: I was responsible for getting the system ready, organizing the experiment, analyzing the results, and drafting the paper. Recruiting the surgeons to participate in the trial was a challenging and time-consuming task—every one of them went through three phases of the study with the washout periods in between. My supervisors, J. G. Bellika and G. Hartvigsen, helped with designing the experiment, interpreting the results, and reviewing the drafts. R. O. Lindsetmo contributed by recruiting the participants, elaborated on the clinical implications of the findings, and participated in the trial.

P3: A. Budrionis, P. Hasvold, G. Hartvigsen, and J. G. Bellika, “Assessing the impact of telestration on surgical telementoring: A Randomized Controlled Trial,” Journal of Telemedicine and Telecare, 2015, doi:10.1177/1357633X15585071 [in press]

Description of the paper: Safety-critical implications of using telestration in surgical telementoring sessions force developed systems to comply with strict regulations [16], [17]. The actual advantages of live video annotation have not been evaluated before and are assumed to be a major improvement to VC-based verbal supervision. Results from a RCT comparing the two mentoring approaches (VC-based verbal supervision versus verbal and graphical supervision) deny the aforementioned assumptions; that is, no significant improvement in clinical and educational outcomes was observed due to the use of telestration. Quantitative measures demonstrated the decreased duration of the mentored episodes; however, telestration deterred the learning progress in the graphically guided scenario. The qualitative measures favored telestration in mentoring sessions, contradicting the numerical findings. The study demonstrated the quantified benefits of telestration in telementoring, denying the global assumptions of a high level of improvement.

Author contributions: I was responsible for preparing the trial system, recruiting the participants, organizing and performing the trial, analyzing the results, and writing the publication. My supervisors, J. G. Bellika and G. Hartvigsen, supported me with the trial design, measurement procedures, and interpretation of the results. P. Hasvold contributed by testing the system and participating in the trial. All of the coauthors reviewed and commented on the manuscript.

1.10 Secondary included publications

P4: A. Budrionis, K. M. Augestad, and J. G. Bellika, "Telementoring as a Service," Scandinavian Conference on Health Informatics 2013, p. 11, 2012.

Description of the paper: The paper provides a brief overview of state-of-the-art in developing surgical telementoring systems and highlights the drawbacks of conventional approaches. A concept of a telementoring service is presented to overcome the mentioned weaknesses, increase the use of the technique, and minimize the maintenance costs. The comparison of popular VC technologies indicated WebRTC as the only alternative for meeting the requirements of the proposed concept. The architecture of a WebRTC-based surgical telementoring service is presented in the paper, followed by an initial evaluation of its performance. Alternative use cases in primary care are discussed, setting the direction for in-depth research.

Author contributions: I proposed the concept of a telementoring service, which was highly supported by my supervisor, J. G. Bellika. We elaborated on the concept, keeping the alternative use cases in mind. K. M. Augestad helped to assess the clinical feasibility of the proposed solution. I performed a review of the VC technologies, adapted the general WebRTC architecture to a telementoring scenario, and wrote the manuscript.

P5: A. Budrionis, G. Hartvigsen, and J. G. Bellika, "Are Mobile Devices Ready for Telementoring? A Protocol Design for Randomized Controlled Trials," eTelemed 2014, The

Sixth International Conference on eHealth, Telemedicine, and Social Medicine, 2014, pp. 197–200.

Description of the paper: The paper presents the protocol for comparing stationary, middle-, and small-sized devices in a surgical telementoring scenario. Trial design is discussed together with technical infrastructure and measurement procedures, giving a comprehensive overview of the planned study and insights into adapting the proposal for future trials.

Author contributions: I proposed the main idea of the trial and composed the manuscript. J. G. Bellika and G. Hartvigsen helped with designing the trial and evaluating the proposed measurements.

P6: A. Budrionis, K. M. Augestad, and J. G. Bellika, "Telestration in Mobile Telementoring," in eTelemed 2013, The Fifth International Conference on eHealth, Telemedicine, and Social Medicine, 2013, pp. 307–309.

Description of the paper: The paper looks into the telestration feature for enhancing communication between the interacting parties in surgical telementoring. The reported study discovered the instability of the laparoscopic camera, which caused the repositioning of annotations; this miscommunicates advice from the mentor and may have critical consequences for the patient. Initial ideas for stabilizing the camera movement and anchoring the annotations are presented, highlighting the gap in current research.

Author contributions: I identified the camera movement problem and evaluated the potential consequences for the patient with K. M. Augestad. Together with J. G. Bellika, we came up with potential solutions and proposals for further research.

P7: A. Budrionis, G. Hartvigsen, and J. G. Bellika, "Camera Movement during Telementoring and Laparoscopic Surgery: Challenges and Innovative Solutions," Scandinavian Conference on Health Informatics 2015 [accepted for publication]

Description of the paper: The paper highlights the underestimated consequences of the laparoscopic camera movement during telementoring sessions featuring telestration. Due to the lack of regulations on the development and application of advancing telementoring systems, they are being used in real-life experiments without properly estimating threats to patient safety. Camera movement causing the shift of telestrations (in other words, inaccurate guidance) is analyzed in the paper. A set of computational techniques, which could anchor the annotations to the artifacts in the video stream, is analyzed. The architecture of a distributed telementoring system capable of dealing with resource-intensive computational tasks on mobile devices is presented.

Author contributions: I performed the literature review and wrote the manuscript. Discussions with my supervisor, J. G. Bellika, helped to define the architecture for distributing the computationally-intensive tasks for live processing. G. Hartvigsen proposed some alternative solutions and reviewed the presented ideas.

P8: A. Budrionis, P. Hasvold, G. Hartvigsen, and J. G. Bellika, "Video Conferencing Services in Healthcare: One Communication Platform to Support All," MEDINFO 2015 [accepted for publication]

Description of the paper: A concept of a web-based VC service was presented in the paper together with a generic architecture for developing clinical VC services. A platform-agnostic solution, having a low usability threshold, proposed a supplement for current VC systems, especially when conferencing capabilities of the end-user device cannot be configured and tested in advance (for instance, emergency telementoring session, doctor–patient consultation, follow-ups of homecare patients, etc.). A surgical telementoring service was developed following the proposed architecture to demonstrate the feasibility of the concept. To ensure that the developed service met the reported latency requirements for surgical telementoring system, a one-way video delay was measured in a dedicated network. The findings demonstrated the feasibility of providing VC as a service for clinical applications.

Author contributions: I designed the VC service, performed the initial implementations and evaluation, developed the latency measurement infrastructure, and wrote the manuscript. G. Hartvigsen and J. G. Bellika contributed to the conceptual part of the architecture and provided their insights on the potential of the proposed solution. P. Hasvold helped with the design of the latency measurement infrastructure.

P9: A. Budrionis, P. Hasvold, G. Hartvigsen, and J. G. Gustav Bellika, "Moving Telementoring to the Web," in International Journal of Computer Assisted Radiology and Surgery, Fukuoka, Japan, 2014, vol. 9, Issue 1 Supplement, pp. 279–280.

Description of the paper: The paper presents the architecture and prototype of a web-based surgical telementoring service (implementing the ideas presented in P4). The initial evaluation results are discussed, demonstrating the validity of the concept. Advantages over the conventional end-user software-based systems are presented, defining the direction for further research.

Author contributions: I designed, developed, and evaluated the web-based telementoring system and wrote the paper. J. G. Bellika and G. Hartvigsen helped with the design and understanding the networking specifics of the NHN. P. Hasvold contributed to the evaluation of the system.

1.11 Papers not included in the thesis

The following papers were published in the scope of the PhD project; however, due to various reasons, are not included in the thesis:

1. K. M. Augestad, J. G. Bellika, A. Budrionis, T. Chomutare, R.-O. Lindsetmo, H. Patel, C. Delaney, and Mobile Medical Mentor (M3) Project, “Surgical telementoring in knowledge translation--clinical outcomes and educational benefits: a comprehensive review,” Surg. Innov., vol. 20, no. 3, pp. 273–281, Jun. 2013.
2. A. Budrionis, K. Augestad, H. Patel, and J. Bellika, “Towards Requirements for Telementoring Software,” Scand. Conf. Health Inform. 2012.
3. K. M. Augestad, T. Chomutare, J. G. Bellika, A. Budrionis, R.-O. Lindsetmo, and C. P. Delaney, “Clinical and Educational Benefits of Surgical Telementoring,” in Simulation Training in Laparoscopy and Robotic Surgery, H. R. H. Patel and J. V. Joseph, Eds. London: Springer London, 2012, pp. 75–89.

1.12 Organization of the thesis

In 1995, Charles D. Friedman proposed a model that summarized the areas of potential contributions in medical informatics [18]. Due to the simplicity and clear distinction between the levels of the tower of achievements (Figure 2), the model maintained its importance over the years.

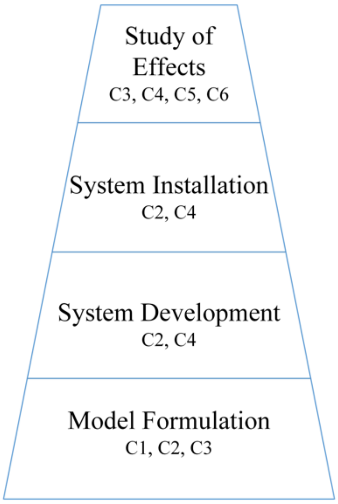

Figure 2. Friedman's tower of achievements in medical informatics [18]. The claimed contributions (C1–C6, section 1.7) are distributed in the levels of the tower.

The following chapters of this thesis are organized according to Friedman's proposal, placing the contributions into the levels of the tower (Figure 2). The theoretical fundamentals together with the conceptual design phase of this thesis form the base layer – model formulation. This is followed by the development and deployment description. System installation is not emphasized due to the specifics of the developed solution – installationless, service-based implementation running in test settings in the scope of the project. A study of the effects consists of three investigations that are unified by the theoretical models that comprise the methodological framework. Every chapter is concluded by a brief summary outlining its highlights. The thesis is finalized by conclusions and suggestions for future research.

2. Model Formulation

This section focuses on establishing theoretical fundamentals for the research project by highlighting the gap in the current knowledge base. The findings from the literature review are discussed and a detailed outlook of regulatory frameworks is presented. Because the scope of the thesis is not directly tied to clinical outcomes, the literature review section is focused on identifying the causes of the generally slow exploration of telementoring and integration into medical practices rather than exploring medical achievements.

2.1 Systematic literature review

To provide a detailed overview of the development in the domain, a systematic literature review was performed following the guidelines by Kitchenham [19] and the PRISMA statement [20]. Three major research databases (PubMed, IEEE Xplore, and ACM Digital Library) were searched using a set of predefined queries ([telestration OR annotation] AND telementoring, [telestration OR annotation] AND teleproctoring, [telestration OR annotation] AND surgery, [telestration OR annotation] AND conferencing, [telementoring OR teleproctoring] AND web). Papers published between 01/01/2000 and 14/05/2015 were analyzed. The review was performed on October 16, 2013; the results were updated on May 14, 2015. Clinically oriented papers, case reports, and reviews providing no or minor technical details were not emphasized. Please see Appendix 4 for a full report.

Twenty papers were included in the full text analysis, all of which focused on the telestration feature within telementoring. The results were classified into technically and clinically oriented contributions.

Clinical publications mostly focused on comparing local and telementored scenarios [21]–[23], confirming no significant differences between the approaches. Video transmission latency was assessed as a quality indicator of the setups, highlighting the complexity of a comprehensive evaluation of the systems [24]. The potential of 3D telestration was questioned, demonstrating faster task completion by junior surgeons in contrast to reduced efficiency of the seniors [25].

Technically oriented papers were concerned about implementing feature-tracking algorithms to anchor the annotations, addressing a challenge that is often overlooked by clinicians while experimenting with remote surgical supervision [26]–[28]. More generic usability studies investigated the visual communication cues, such as pointing and drawing, in distributed teamwork [29]–[31]. The studies demonstrated the importance of visual interaction techniques in collaboration over distance scenarios. Socio-technical aspects of distributed surgical teams were also studied, highlighting the organizational challenges telementoring systems face [32].

2.2 Surgical telementoring: State-of-the-art

The first reports on telementoring date from the 1960s, when Dr. Michael Ellis DeBakey performed the first in history open heart surgery transmitted overseas by satellite [13]. His success and the assumptions for unexplored potential worked as an initial impulse for the development of telemedical tools. Advances in ICT brought new players to the medical system market, which for many years was dominated by well-known vendors, producing dedicated and highly hardware-restricted systems. Now, low-priced and highly efficient ubiquitous technologies together with high bandwidth that covers even remote areas are reshaping the development and deployment of clinical systems. In-house-built solutions and open-source projects are competing with the market leaders to deliver the infrastructure to support surgical telementoring [14].

If we look at the big picture of the reported research related to remotely guiding a surgeon during an operation, a surprisingly high number of case reports can be found. The numbers have increased over the years and have been summarized more than 20 times in literature reviews (PubMed, May 14, 2015). The focus is less extensive in the technology-oriented research databases (IEEE Xplore and ACM Digital Library, May 14, 2015), prompting the gap between technology and clinical use of the approach.

Clinically oriented research highlights the use of telementoring mostly in laparoscopy [33], with extra attention paid to robotic surgery [34], [35]. The medical outcomes of the approach are of high importance for moving the domain forward. Evidence supports the feasibility of telementoring replacing on-site mentoring in numerous scenarios [10], [36], [37]; the number of successful cases is overwhelming [13], [33].

Technically oriented literature is more directed towards low-level technical problems like data transmission, bandwidth limitations, and routing mechanisms [38]–[40]. Attention to telestration capacity combines image processing mechanisms with surgical telementoring to increase the accuracy of the graphical supervision [26]–[28]. Focus on large-scale solutions, usability, and integration into clinical practice is minimal [41].

Defining the state-of-the-art in surgical telementoring is a complex task. The inconsistencies in reporting and development have produced a large quantity of publications; however, they are missing a systematic development of the domain. Telementoring, which began as broadcasting a video of the surgical procedure to the remote recipient, evolved to surgical decision support and navigation systems, offering more than on-site mentoring. The combination of multiple modalities, including but not limited to medical imaging, tissue tracking, and 3D modeling, aims to revolutionize operating rooms and surgical departments [42]–[44].

However, regardless of the numerous optimistic ideas, the reality is different. Only the major remote presence technology vendors can offer sustainable telementoring solutions (da Vinci Surgical System Intuitive Surgical[2]; RP-Vantage InTouch Health[3]), while the continuity of the research-initiated services is non-existent. None of the existing telementoring solutions provide an infrastructure-agnostic service, and they continue to rely on the designated mentoring hardware and preconfigured setups.

Integration is another weakness of the existing approaches. The variety of equipment in the operating rooms and the ability to utilize legacy interfaces and develop new workflows of telementoring (teamwork-based mentoring, broadcasting nodes for education purposes, etc.) is limited. Telementoring is still visualized as a one-to-one preplanned session, while adaptation to the novel user’s needs is lacking.

Managing costs while making operating rooms telementoring-capable is another challenge. For example, monthly costs for one remote presence unit could range from $1,000 to $5,000 [34], [45], excluding acquisition and salary of the mentors. A da Vinci surgical system costs around $2 million, not counting the running expenses and questionable improvement of patient outcomes [46]. Such considerations make telementoring a luxury, especially for smaller, rural hospitals, which could benefit the most from the technique.

The findings above call for major architectural and organizational changes to bring telementoring to its full potential. An infrastructure that is flexible, highly available, open for extensions, and able to scale is required to benefit from the technique. The published research proves the validity of telementoring in general; however, drawing quantitative conclusions on the benefits requires a higher level of standardization globally [10], [36], [37]. The discussed inconsistencies in the current body of knowledge on telementoring point to the potential obstacles preventing it from becoming a common practice in operating rooms around the world.

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[2] http://www.intuitivesurgical.com

[3] http://www.intouchhealth.com/products-and-services/products/rp-vantage/

Major findings

The number of case reports in telementoring is increasing. The reported systems range from freeware to commercial hardware-based VC equipment. The performed experiments are highly specialized, preventing generalized conclusions. The systems are developed and deployed to prove the concept; however, they neither scale, nor are continuously employed in testing or clinical workflows (based on the lack of continuous studies). In other words, a global vision of telementoring is missing. The common features describing such systems are orientation towards client–server software architecture, preconfigured end hardware, and planned supervisions. Such configurations work well for research purposes, but they do not reach the maturity for integration into clinical workflows as tools for daily use [47].

The experimental studies look into telementoring from the clinical point of view; technical details enabling the reproduction of the reported results are often limited. The research is dominated by clinical experts who aim to study and report on the impacts of the technique on the selected clinical procedure. Nobody denies the contributions of such studies; however, the long-lasting explorations lack a global direction. Telementoring has been proven to be a beneficial tool in the operating room [10], [36], [37]; however, to explore its full potential, a large-scale service with high availability needs to be established. Coordination aspects of such an infrastructure need to be addressed, establishing a cross-institutional collaboration on the regional, national, and international level.

A lack of common technical infrastructure and good practices in developing telementoring systems has caused the current situation. Every research team started the implementation from scratch, based on the specifics of the environment and the procedure they were focusing on, and finished with a proof of concept implementation in highly simplified settings. This may be why such systems have not become the daily tools of surgical departments.

2.3 Regulatory frameworks

The missing technical definition of telementoring, including the description of the assisting features, makes mapping it to the regulations for clinical use difficult. The regulatory documents do not target the specific case of telementoring due to their generic focus. A decision of whether surgical telementoring needs to comply with the restrictive regulations of medical devices is often made in favor of easier progress. In other words, telementoring is claimed to be a communication module that does not need to follow medical device regulations.

From a technical point of view, telementoring is a specifically tailored VC system that provides the remote party with live progress from the operating room. Mechanisms supporting live verbal communication between the endpoints are featured; graphical feedback functionality (telestration) is often utilized to avoid ambiguities in describing locations in the live video stream. Enabling the remote expertise to influence the procedure performed in the operating room is the main purpose of the technique, creating concerns about patient safety and confidentiality [2], [13], [48].

This section explores the international regulatory documents in order to map them to the features of telementoring systems to clarify what level of control should be enforced in the development and evaluation of remote surgical supervision tools.

2.3.1 The European medical device directive

MEDDEV 2.1/6 [16] and its predecessor, Directive 93/42/EEC [49], defines a medical device as an "(…) instrument, apparatus, appliance, software, material or other article, whether used alone or in combination, including the software intended by its manufacturer to be used specifically for diagnostic and/or therapeutic purposes and necessary for its proper application, intended by the manufacturer to be used for human beings for the purpose of (...) diagnosis, prevention, monitoring, treatment or alleviation of disease (...)" [16]. The above definition counts on the manufacturer to define the intended purpose of use of the device in clinical settings. However, stand-alone software capable of providing "immediate decision triggering information or support for healthcare professionals" [16] qualifies as a medical device. Based on the technical definition of telementoring (section 2.3), it should be treated as a means for providing support and decision-triggering information for surgical personnel.

One could argue that a basic VC link between the operating room and the remote mentor only replaces a phone call and serves as a communication module. The assumption may be right as long as the functionality of such service is not supplemented by the additional features (telestration, image processing, navigation capacity). The intended purpose of such a system is to provide decision-triggering information for the on-site surgeon and to enable the remote party to influence the flow of surgery in the operating room. Based on the classification criteria (MEDDEV 2.1/6 [16]), the discussed system is a medical device.

2.3.2 US Food and Drug Administration (FDA)

In addition to the European regulations, the FDA has defined a set of control documents that can be applied to telemedical systems in general. The FDA regulates the use of devices within clinical settings based on the potential risks they introduce [17]. Most telemedical systems are regarded as Class II (moderate risk) medical devices due to their intended use for active patient monitoring, transmitting/receiving, and storing real-time video and audio as well as patient data [50]. Communication modules are also considered to be Class II medical devices; however, they are exempted from premarket notification procedures [51].

Regardless of the distinction between communication modules and surgery-influencing equipment, telementoring systems fall within the category of a Class II medical device. The same conclusion was made by Intouch Health[4], a major vendor of remote presence systems, while developing their telementoring solution [17].

Major findings

Regardless of the absence of regulations directly targeting telementoring systems, the analysis of the legal frameworks has suggested that remote supervision systems fall within the regulations of medical devices, prompting the following considerations:

1. All development and investigation has to follow the regulations, starting from preclinical testing and being approved as a medical device, to progress to the clinical investigation [52].
2. The path from the idea to the actual use in clinical settings becomes much longer. It also hinders the chances of research projects reaching the level of clinical investigation.
3. Criticism of the published clinical studies in telementoring that disregard regulations, patient safety, and confidentiality concerns is necessary. So far, both researchers' and publishers' focus on following the regulations seems to be minimal.

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[4] http://www.intouchhealth.com/products-and-services/products/rp-vantage/

2.4 What do the surgeons expect from telementoring?

Inter- and intra-hospital communication are an important part of healthcare workers' duties [53]. While the actual scale of the interactions is highly dependent on the analyzed workflow, the knowledge of the communication patterns in clinical settings seems to be insufficient [54], [55]. Telementoring adds an extra communication channel, emphasizing the visual component, to the existing stack. It also requires more sophisticated end-user hardware than the well-established pager infrastructure [56].

Telementoring is considered to be a "surgical tool of the future" [9]. This is a perfect definition of the expectations of the surgical personnel towards the technology. Telementoring must be easy to use, highly available, and reliable if it is to become a common practice. On the other hand, telementoring is not a complete solution. In a simplistic scenario, it is an extension of an emergency telephone call to a remote colleague asking for his or her opinion. According to Coiera [57], social and technical system needs are inseparable; thus, the improvement of a simple telephone-based communication link should not be over-engineered; rather, it should maintain the features that made the approach attractive to clinicians in the first place while improving the drawbacks. Telementoring should, first of all, have as low usability threshold as a telephone does. The benefits of the visual component in surgical decision-making should be a sufficient impetus encouraging more extensive use.

Telementoring has the potential to offer more than on-site mentoring, and in the words of Hollan and Stornetta, to go "beyond being there" [58]. Modalities not available in the operating room come into play, enhancing collaborative efforts. Live telestration, overlay of 3D models, navigation, and image analysis are just a few techniques that could make telementoring preferable to on-site and verbal guidance [26], [59]–[61].

However, the published research (section 2.1 and 2.2) shows that the approach took a different direction—strictly defined settings and planned sessions have been the main focus of studies thus far. Maybe this is why telementoring, having more than 50 years of success stories, has never become an established clinical practice.

2.5 Telestration in surgical telementoring

The ability to annotate live video content has mainly been exploited in reporting weather forecasts or commenting on sports. A simple tool to improve localization tasks in dynamic surroundings, often lacking distinctive features for anchoring (Figure 3), has also attracted the attention of clinical personnel and vendors of surgical telementoring systems [14], [62].

Experimentation with telestration while mentoring leads to a better understanding of the complexity of surgical videos, representing the progress of the procedures. The dynamics of this stage is one of the main factors making the simple feature of video annotation a complex functionality with critical implications. Continuous and unpredictable camera movement is an integral part of laparoscopic procedures that may reposition the annotations produced by the mentor and result in inaccurate guidance. It calls for mechanisms that attach the annotations to the locations they were placed on to prevent the displacement. The specifics of the laparoscopic videos (constant, unpredictable motion of the surrounding soft tissues, surgical tools appearing in the operative field, body liquids splashing on the camera lens, and lacking reidentifiable features in the scene) make the camera movement problem even more challenging to solve. It becomes extremely important to minimize patient safety risks while experimenting with telementoring in clinical settings [48].

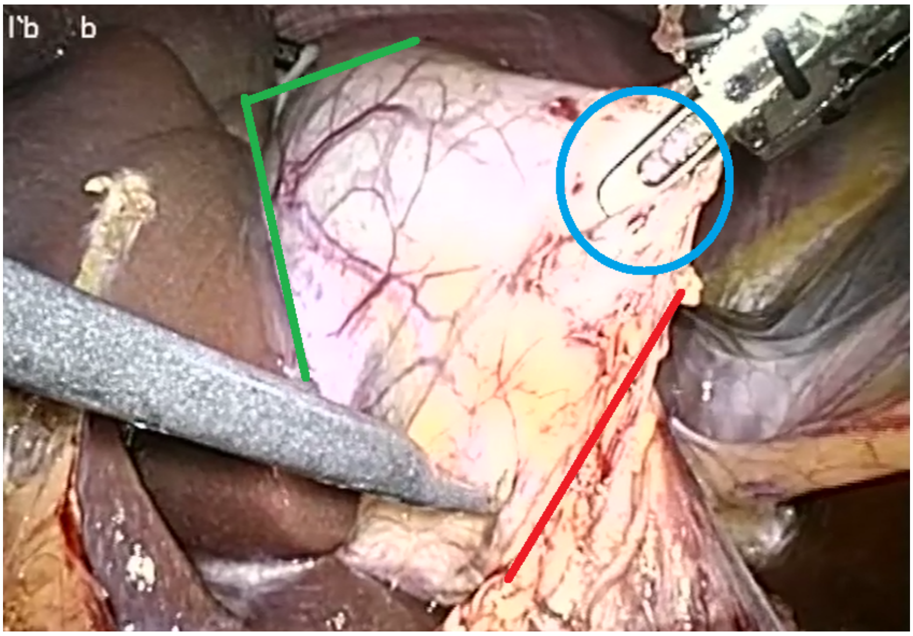

Figure 3. Surgical telestration [62].

Regardless of the assumptions of the benefits telestration brings to telementoring, no support for the claims was identified. Analysis of the most important publications reporting the use of live video annotation in remote surgical supervision did not identify any attempts to evaluate the outcomes directly related to the use of telestration [62]. This highlights a gap in the current research, which this PhD thesis further explores.

2.6 Rethinking telementoring

VC is the fundament for telementoring and many other telemedical services. The deployment of VC-based clinical systems emphasizes the high usability threshold for end-users, thus prompting the research on telementoring to rely on preconfigured designated mentoring hardware. This section provides an overview of the evolving VC systems from the deployment perspective and proposes the design of the platform-agnostic telementoring system.

2.6.1 Evolution of VC

VC has evolved significantly from its first introduction; however, its definition and functionality have hardly changed. Simultaneous full-duplex video and audio interaction has been implemented in numerous settings. From the deployment point of view, three main generations of VC systems can be distinguished (Figure 4).

The technology started from the idea of connecting one location to another by utilizing dedicated networks and hardware. The hardware-heavy solution did the job well, ensuring a link between two (or more) locations (Figure 4, A). However, the solution lacked flexibility in including remote parties without investing in the expensive end-user equipment. Software-based VC nodes utilizing common hardware were a straightforward solution to improving availability (Figure 4, B). In this case, two (or more) devices were connected to provide a communication medium for the remote parties independent of location (a device-to-device link). The next logical development is enabling the actual person-to-person connection without attaching it to any infrastructure between the two (Figure 4, C). In other words, VC infrastructure should be delivered as a service that is accessible from the device of the users' choice without hosting any specific software on the client's side. It plays a major role in employing the computationally lightweight hardware (tablets, smartphones) as the endpoints of the link.

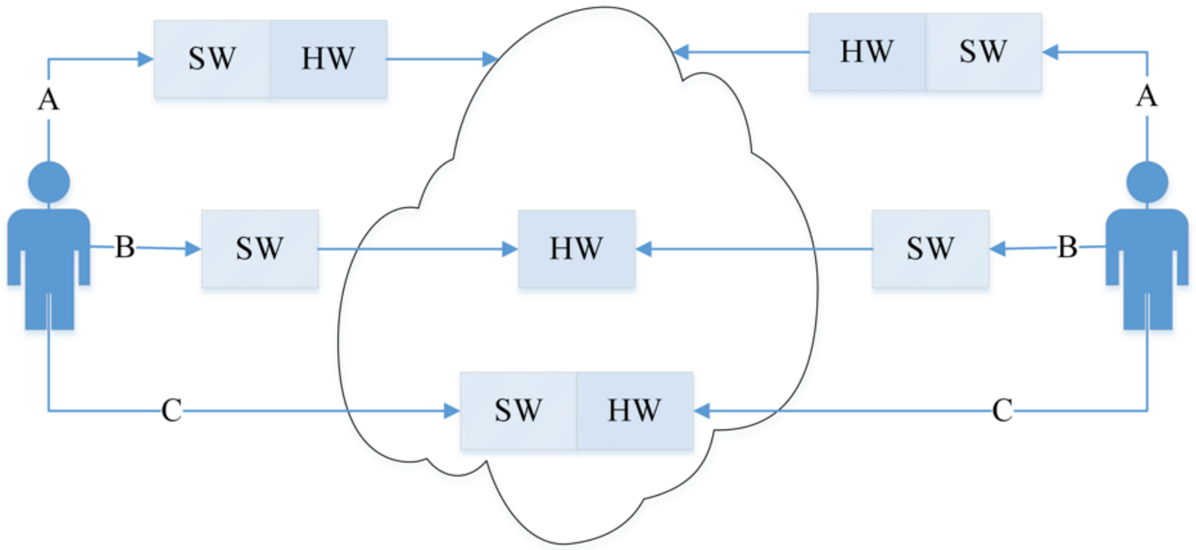

Figure 4. Evolution of VC: A = location-to-location link utilizing hardware-based solutions on both client sides, B = device-to-device connection featuring client-side software-based systems, C = person-to-person communication over VC service.

Earlier attempts to develop surgical telementoring systems utilized heavy hardware and software endpoints (Figure 4, A and B). The focus of this project is the next generation of telementoring—a seamless person-to-person link between the operating room and the remote expert.

In numerous use cases, the endpoints of the link are not aware of each other in advance. Simply speaking, the participants are represented by hardware that was not preconfigured to access the meeting (installation of VC-specific software is considered to be preconfiguration). Handling an emergency telementoring session is a perfect example of the discussed scenario, highlighting the limitations of the current infrastructure: while the operating room is a controlled environment, to ensure the connectivity for the remote expert, possibly using a device that he or she had available at the critical moment is complicated. A solution that supports ad hoc telementoring links is lacking (Figure 4, C).

2.6.2 VC service

The previous section presented the idea of a cloud-hosted VC infrastructure enabling seamless person-to-person interaction regardless of the underlying hardware. Comparison to the conventional VC systems elaborates upon the proposed approach.

To establish a connection between remote peers in the most common case (device-to-device, Figure 4, C), VC-specific software running on the endpoints is essential. The need for installs and updates increases the usability threshold for the user, especially in emergency scenarios.

Centralized maintenance of the end-user devices generates additional costs, increasing when scaling up. Voiding the mentioned limitation transforms the device being used to establish the connection into a consumer of a VC service, making the link end-user hardware-independent. In other words, low-usability-threshold platform-agnostic VC links become a reality.

The service is being developed to serve communication needs within the NHN[5], including connections in which at least one of the parties is outside of the secure network. The initiative builds a VC gateway connecting healthcare institutions to the outside world. It opens unlimited possibilities for research, education, and improvement of the quality and availability of clinical services.

2.6.3 Generic architecture

Reusability of the proposed VC gateway is of great importance in developing clinical VC services. To fully exploit its potential, a generic architecture embracing the flexibility and reusability of the proposed approach is presented.

The earlier-discussed general-purpose VC service is designed to become the foundation of a wide range of clinical applications (Figure 5). It supplies the third parties with the core functionality, while the case-specific features are implemented at the application level. Meeting the regulations of the medical domain and handling the connectivity within the NHN becomes the responsibility of the VC service provider; the third parties are supplied with an API to access the core functionality.

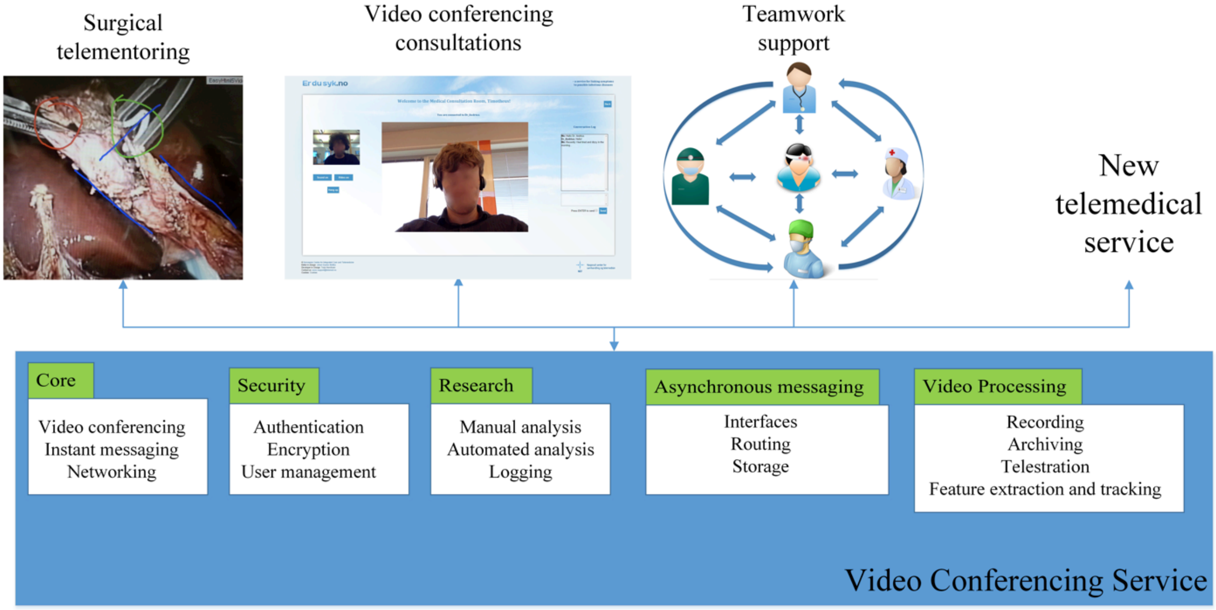

Figure 5. Generic architecture of the VC service [5].

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[5] https://www.nhn.no

Scalability and seamless integration into clinical workflows are the key features of the service—such properties are often identified as major weaknesses of former solutions [12]. In addition to the core functionality, a set of toolboxes is available for API users (Figure 5):

1. Security: implementing additional security measures to the built-in mechanisms.
2. Research: supporting manual and semi-automatic tools for video analysis.
3. Asynchronous messaging: providing an email-style messaging platform.
4. Video processing: including functionality for video storage and real-time enhancement.

The combined set of features provides the foundation for a wide range of research-oriented clinical applications that use VC. Currently, only the core functionality has been developed and reused.

2.6.4 Authentication and access control

Mechanisms for user authentication and access control were discussed; however, they were not implemented in the scope of this project. While not being essential in the proof of concept stage, they are of major importance in real-life settings. Based on the Norwegian regulatory documents on information security in healthcare [63], a comprehensive risk assessment should estimate the required level of security for applications.

In the case of telementoring, it is important to note that videos from laparoscopic procedures are anonymous and contain no data that could identify a patient. Support for a level 4 bankID-based authentication [64] is planned when beginning large-scale clinical studies.

2.6.5 Telementoring service in the healthcare network

Based on the findings from the published body of knowledge on telementoring, a concept of telementoring service in the healthcare network is suggested. It aims to standardize the attempts to develop remote mentoring systems by offering publicly available infrastructure that allows the additions of case-specific features. The main challenges addressed by the telementoring service are discussed below.

1. *Standardization of telementoring infrastructure*. The reuse of the core functionality to develop VC services ensures the comparability of the produced research results in contrast to the fragmented current reporting of the studies. It balances the service provider-controlled core technology and gives freedom to third-party API users to customize the interfaces based on the project needs.
2. *Usability*. The disruptive features of the suggested VC service void the need for dedicated mentoring hardware. A low usability threshold for the participants ensures seamless person-to-person connections regardless of the underlying technical infrastructure.
3. *Connectivity*. Establishing VC links crossing the boundaries of the secure networks in hospitals is a major challenge when implementing large-scale clinical services. Specifically, configured firewalls, proxies, and other advanced equipment that ensure a high level of network security create a bottleneck in increasing the availability of the services and enabling them to cross organizational barriers.
4. *Legal regulations*. Studies often ignore regulatory frameworks issued by the European Commission and FDA (discussed in section 2.3), leading to unapproved telementoring systems being tested in clinical settings [65], [66]. Due to the missing legislation explicitly targeting telementoring, patients might face unnecessary risks.
5. *Large-scale service*. Regardless of the potential of the technique, telementoring in a surgical department scope is a luxury. It is unlikely to have one of a few available domain experts on call for mentoring instead of performing surgeries. A large-scale service that crosses institutional barriers is required to succeed. The same on-call expert covering telementoring demand in a country scope is no longer an unaffordable luxury.
6. *Integration into current medical systems and clinical workflows*. The number of ICT systems in hospitals is constantly increasing. Interoperability is often limited, increasing support and maintenance costs. Service orientation ensures the easy integration of telementoring into web-based clinical systems without introducing additional software solely dedicated to remote supervision. Moreover, the end-users are not supplied by another device for mentoring purposes in addition to the ones they already have and carry around.

Providing the core VC functionality as an integrable service addresses the discussed topics on a large scale instead of dealing with them at a particular implementation level that is often limited to a single department within a hospital.

2.7 Summary

Chapter 2 laid the theoretical fundament for the research project. Literature review looked into the published research in telementoring, mostly focusing on the technical aspects. Focus on research-based systems having limited continuity was concluded. Only major remote presence equipment providers were able to offer sustainable solutions that met the international regulations for surgery-influencing systems. Interest in ad hoc emergency telementoring scenarios was non-existent, probably due to technological limitations. Integration into clinical practices is of high importance to ensure the continuity of the service; however, existing telementoring initiatives did not succeed in becoming the daily tools of the surgeons.

The high usability threshold for the end-users was emphasized as one of the factors deterring progress: designated hardware, complex connectivity, and high maintenance costs encourage sticking to the established telementoring approach (a phone call). Regardless of the ease of use, phone-based mentoring lacks the visual dimension that is critical for increasing the quality of the process.

To overcome the mentioned limitations, a concept of surgical telementoring service was proposed. It features a platform-agnostic VC channel that provides a customizable gateway to the operating room. It minimizes establishment and maintenance costs for surgical departments and standardizes VC-based communication to deliver a low usability threshold system. This chapter summarized the conceptual part of this thesis.

3. System Development

This chapter focuses on implementing the ideas discussed in chapter 2. Cases of surgical telementoring will be explored in detail in the following sections.

3.1 Selecting the VC framework

In order to select the VC framework for developing a remote mentoring service for surgeons complying with the proposed architecture, a comparison of popular VC technologies was performed. Scalability, maintenance costs, security, usability, and integration were emphasized while analyzing the differences of the implementations. The following aspects were taken into consideration:

1. A need to install/update software on the client's device to facilitate a telementoring session.
2. Supported software platforms.
3. Control over hosting/routing infrastructure.
4. Connection properties between the interacting parties.
5. Maintenance and use costs for the department (hospital) to run such a service.
6. A need for network/hardware configurations to establish the connection.
7. Licensing of the framework.

Popular VC systems that do not use dedicated client-side hardware were included in the comparison. The main goal of the study was to simplify the use of VC-based services—client-side software installations and updates were regarded as an unnecessary complication that introduced an additional burden for the service provider and the end-user. Having the control over the routing and data processing infrastructure between the interacting parties is important for security-related considerations. Moreover, a scalable centralized maintenance and support mechanism is the way to manage additional costs for the collaborating projects and institutions. The results from the comparative study, performed on February 20, 2014, are presented in Table 1.

Table 1. Comparison of popular VC systems (results collected on February 20, 2013)

	WebRTC [67]	Google Hangout [68]	Skype [69]	Adobe Connect [70]	Cisco WebEx [71]
Software install/update on client device	No	Yes (browser plugin)	Yes	Yes (flash player)	Yes
Supported platforms	Windows, Linux, Mac OS, Android	Windows, Linux, Mac OS, iOS, Android	Windows, Linux, Mac OS, iOS, Android	Windows, Linux, Mac OS, iOS, Android	Windows, Linux, Mac OS, iOS, Android
Hosting/routing infrastructure is fully controlled by the service provider	Yes	No, controlled by the vendor	No, online peers are used as infrastructure	Yes	Yes
P2P media connection between the clients is used	Yes	No	Yes, specifically tailored by the vendor	Yes	Yes
Maintenance and use costs	Very low (server maintenance)	-	Low (subscriptions)	Medium (monthly subscriptions, hosting infrastructure)	Medium (monthly subscriptions, hosting infrastructure)
Need for network/ hardware configurations	No	No	No	No if acquired as a service; yes if deployed within the existing infrastructure	No if acquired as a service; yes if deployed within the existing infrastructure
Open-source implementation	Yes	No	No	No	No

Based on the simplicity of establishing the connection, maintenance, and customizability, WebRTC was chosen as the best-fit technology for implementing the ideas proposed in section 2.6. Apart from supporting the iOS platform, WebRTC met the most of the requirements for developing a surgical telementoring service.

The choice of the technology could be questioned due to the immaturity of WebRTC (February 20, 2013) in comparison to other (better established) VC solutions. However, major usability improvements that are delivered by the web-based VC and an active support community encouraged using WebRTC as the fundamental technology in this PhD project.

3.2 WebRTC: The fundamentals for clinical VC services

WebRTC represents the novel initiatives of Google to revolutionize the development, application, and integration of VC systems [67]. The provided open-source implementations enable using a standard web browser that utilizes only built-in APIs as a client for VC sessions (browser support is currently limited to Mozilla Firefox, Google Chrome, and Opera, which run on Windows, Mac, and Android platforms [72]). Not only is it a major improvement to the usability of current VC systems, it also supports the conceptual architecture for developing clinical VC services (presented in section 2.6.3). A comparative analysis (Table 1) highlighted the advantages of WebRTC over the well-established technologies.

Open-source EasyRTC [73] JavaScript libraries were used to establish the general purpose VC service. Technical details of the implementation were discussed by Kampik [74]. The surgical telementoring service accessed the generic VC infrastructure over a public API. A telestration toolbox and a graphical user interface customization supporting the variance of screen sizes and resolutions on the remote side were handled by the telementoring server following the design of the generic architecture (Figure 6).

To support the mentoring needs of the surgeon, the equipment in the operating room was supplemented with a workstation that facilitated input for the video signal from the laparoscopic rack and an LCD display for displaying video and annotations. The workstation runs a browser-based operating room client, transmits laparoscopic video to the remote node, and combines video with the annotations produced remotely by the mentor. At the same time, it enables audio conferencing between peers. The generic VC infrastructure is hosted at NST and is accessed over the HTTP/HTTPS port. It consists of EasyRTC signaling, Session Traversal Utilities for NAT (STUN) [75], and Traversal Using Relays around NAT (TURN) servers [76], [74].

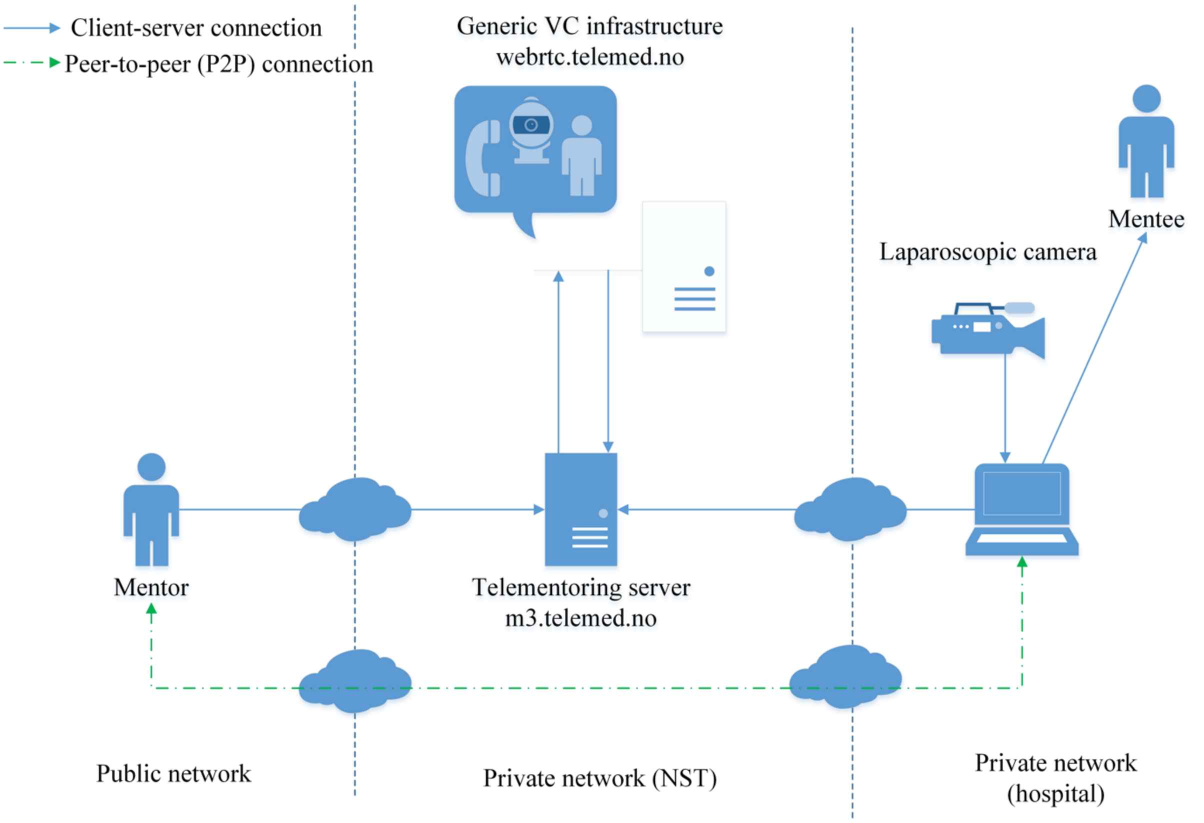

Figure 6. Components of the telementoring service [47].

At the proof of concept stage, the functionality was limited to one-way video broadcasting (operating room -> remote mentor) supplemented by telestration capacity (mentor -> operating room) [48]. In other words, video from the laparoscopic camera from the operating room was transmitted to the device of the mentor. Audio interaction between endpoints as well as freehand sketching on the live video stream produced by the mentor were enabled; graphical guidance was represented on an additional monitor in the operating room.

Crossing the border of the NHN is the major challenge; it is currently (June 4, 2015) unresolved. Regardless of WebRTC's promise to handle complex network topologies, the restrictive settings of the NHN caused inconsistencies in establishing the connections [74]. A lack of support in identifying and solving the networking questions resulted in not using the NHN in later experiments[6].

The current implementation utilizes OSI transport layer security mechanisms to ensure data confidentiality and integrity. The interaction is initiated by the exchange of session data

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[6] Currently (June 4, 2015), the NHN is working on major infrastructure updates that hopefully include support for WebRTC, among other enhancements.

between the interacting nodes and signaling server. SSL/TLS over HTPPS [77] secures the data exchange, preventing security breaches. DTLS/SRTP [78] is used for media traffic encryption to prevent interception of the video content. The built-in security mechanisms ensure end-to-end data encryption and integrity; application- and user-level access control and authentication schemes were not implemented in the current prototypes.

3.3 General workflow

The assumptions regarding the architecture discussed in chapter 2 were maintained throughout the development phase (Figure 6). The proposed infrastructure consists of two major parts:

1. Generic VC service (webrtc.telemed.no). This handles VC-related features such as transport layer security, discovery of peers, and traffic routing.
2. Surgical telementoring service (m3.telemed.no). This customizes the VC channel provided by the general purpose service and adds telestration functionality.

The interaction is initiated by the mentee when supervision is needed in the operating room. An external messaging protocol (email, text messaging) is required to reach the mentor before he or she connects to the mentoring server. The notification message contains a unique web hyperlink for establishing the session. After both parties are connected to the server and exchange of session data has occurred, a P2P link between the nodes is established (Figure 7). In the current version, data logging and recording is performed on the operating room side. Moving these to the EasyRTC server to improve the management of the collected data is planned for the future; however, this is challenging due to the nature of the P2P connection, which excludes the server for media traffic.

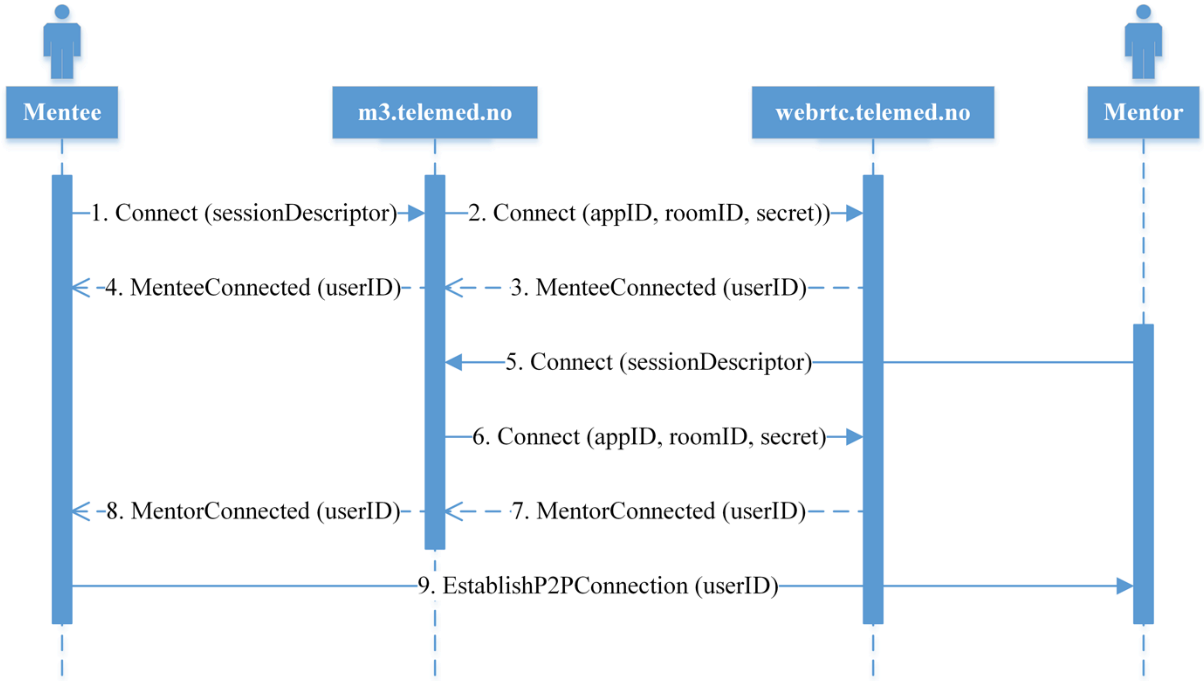

Figure 7. Establishing a P2P connection.

3.4 Telestration toolbox

A live video annotation toolbox (implemented in JavaScript) was integrated into the surgical telementoring service prototype. The functionality of the toolbox includes capturing the touchscreen/mouse input over the live video, scaling according to the resolutions of the interacting devices, and overlaying the produced annotations over the video (Figure 8). A WebRTC text-messaging channel transports the telestration-related data between the mentor and mentee. The current version supports one-way (mentor -> mentee) telestration, which could also be extended to support annotations originating from the operating room. However, due to sterility constraints, usability of the feature by the surgeon is doubtful.

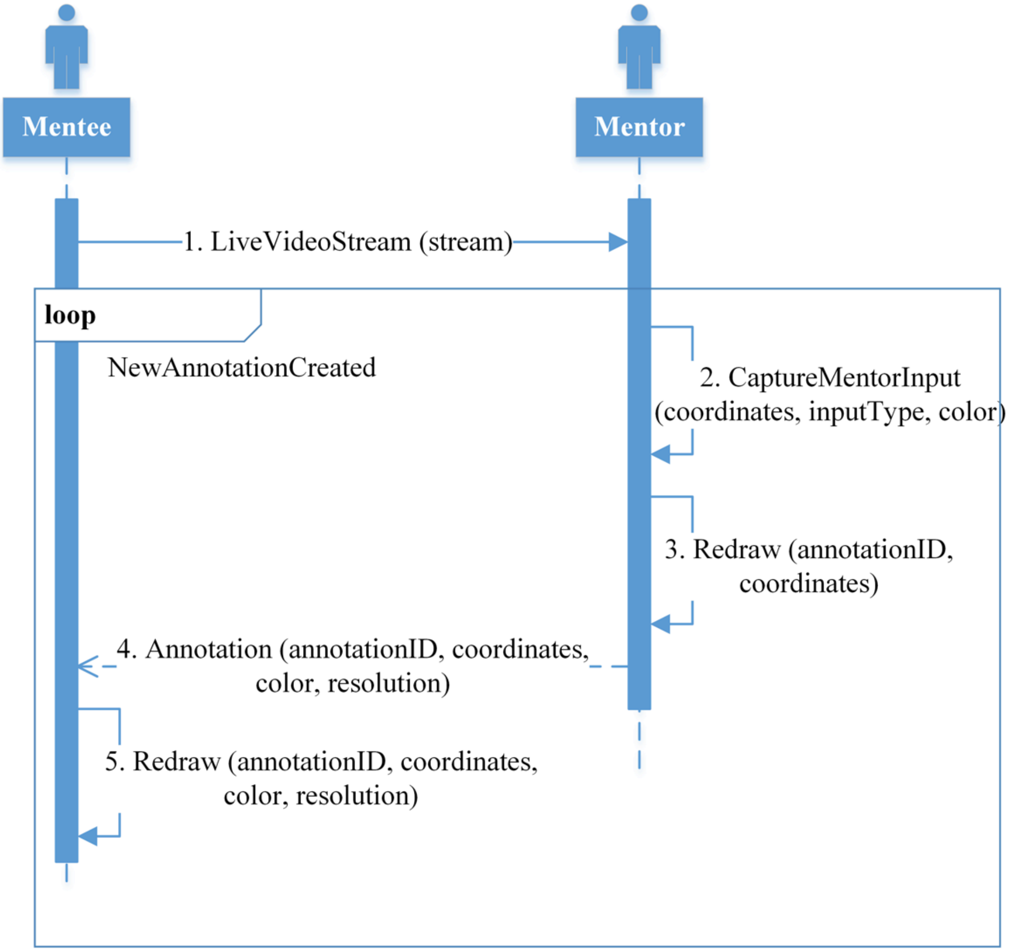

Figure 8. Sequence diagram of the telestration toolbox.

3.5 Summary

Chapter 3 sums up the activities that transformed the conceptual ideas discussed in chapter 2 into an operational system.

A comparison of popular VC technologies identified WebRTC as a best-fit technology to meet the requirements of the novel surgical telementoring system; it provided the technological fundament for the service. System deployment was discussed together with the operational scenario. Implementation of the telestration feature was emphasized.

A code for the developed system is attached to the manuscript.

4. Study of Effects

The top section of Friedman's tower of achievements [18] analyzes the impacts of the modeled and developed systems, supporting the lower-level contributions with the experimental findings. This section clarifies the methods used in the studies and summarizes the major findings, mapping them to the research questions and contributions of this thesis.

4.1 Materials and methods

This chapter presents the big picture of the research methodology, linking the performed studies to the theoretical framework. Trial-specific methods are discussed in the corresponding sections.

The research project demonstrated the feasibility of providing surgical telementoring as an online service. In addition, it studied the influence of telestration on the mentoring process and its outcomes. An evaluation framework was followed as the methodological foundation [62]. The theoretical models divided the impacts of telestration into clinical and educational (Figure 9). The influence of educational impacts on clinical outcomes was not investigated in the scope of this thesis. Relations between the concepts were studied in non-clinical RCTs to observe, measure, and quantify the aforementioned impacts.

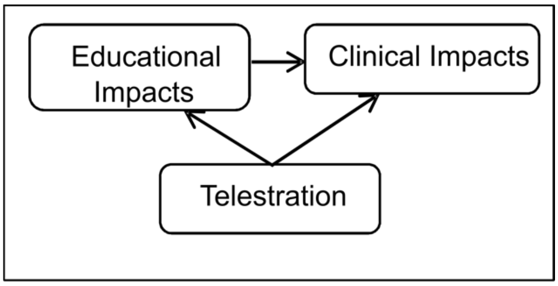

Figure 9. Impacts of telestration on surgical telementoring [62].

It was assumed that the use of telestration decreases the duration of surgical training, resulting in higher scores in a shorter amount of time (Figure 10). This hypothesis was based on the improved communication between the mentor and mentee and the reinforced memory effects caused by the graphical modality in the learning process [62].

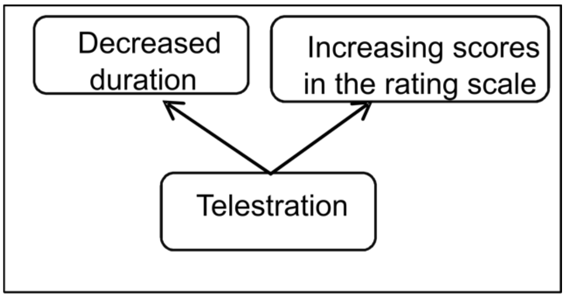

Figure 10. Educational outcomes of telestration [62].

The clinical outcomes emphasized the increasing accuracy of the mentoring process due to the minimized ambiguity of the mentor's commands. In relation to the expected shorter mentoring time, the overall duration of the procedure is expected to decrease (Figure 11).

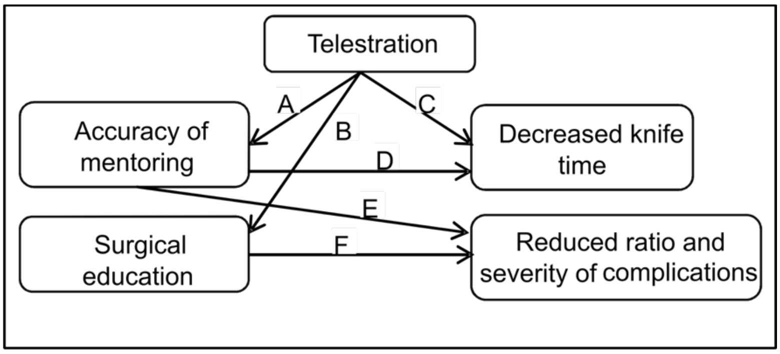

Figure 11. Clinical outcomes of telestration in telementoring [62].

The studies focused on the direct impacts of telestration on the defined concepts (Figure 11, A, B, and C). The elaborated methodologies, measurement procedures, and results are explained in sections 4.3 and 4.4, which specify the performed studies.

4.2 Study I: Demonstrating the feasibility of the telementoring service

Relevant papers: P2, P4, P8

Studied research question:

Q1: Do modern web technologies provide a sufficient foundation for developing a surgical telementoring service?

The literature review (section 1 and 2) indicated no previous attempts to develop a web-based surgical telementoring system. A published quality indicator of one-way video latency [15] was chosen as a benchmark to evaluate the proposed architecture and the prototypical implementation before proceeding with RCTs.

4.2.1 Method

To validate the prototypical implementation, an end-to-end latency measurement in test settings was performed. A one-way video delay, introduced by the developed system, was targeted. A dedicated wireless network served by a single router (802.11g) imitated the infrastructure between the peers. The operating room client node was started on a Macbook Pro (late 2013) I5 8GB RAM computer using video feed from a built-in HD camera and was accessed from a 10.1” Asus MeMO full HD 1GB RAM tablet computer running Android 4.2.

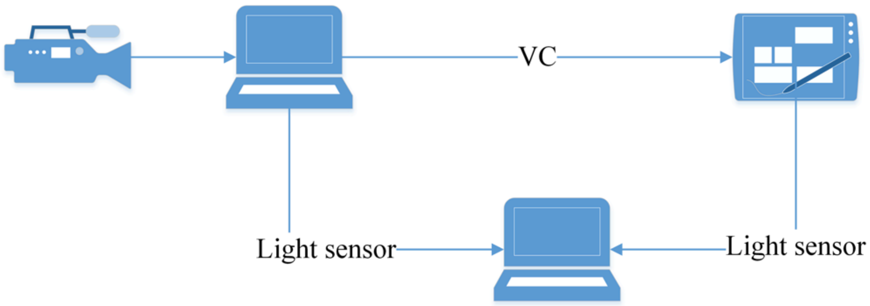

Figure 12. Latency testing scheme.

Two identical light sensors were attached to the screens of the interacting devices to capture the differences in lighting. A programmable Arduino circuit board [79] connected to another computer logged the changes in lighting while a white sheet of paper was put in front of the camera of the broadcasting device (Figure 12). The difference in time between when the sensors were triggered was considered as one-way video latency. Network traffic was imitated via a P2P file download. Three rounds of measurements consisting of > 30 iterations each were performed for every tested network load [5].

4.2.2 Results

Measuring the latency of the developed system aimed to demonstrate the validity of the proposed architecture for developing a surgical telementoring system as well as to compare the video delay to the published maximum threshold of 500 ms for not having the influence on surgical task completion [15]. The measures averaged at 226.7 ms under perfect network conditions and 325.7 ms and 338.7 ms under 0.5 and 1 mb/s data traffic, respectively (Figure 13). The 500 ms limit was never reached in traffic-free conditions, while the latency increased together with the load of the network. Regardless of the extreme values, the average expected measure were acceptable (< 500 ms [15]).

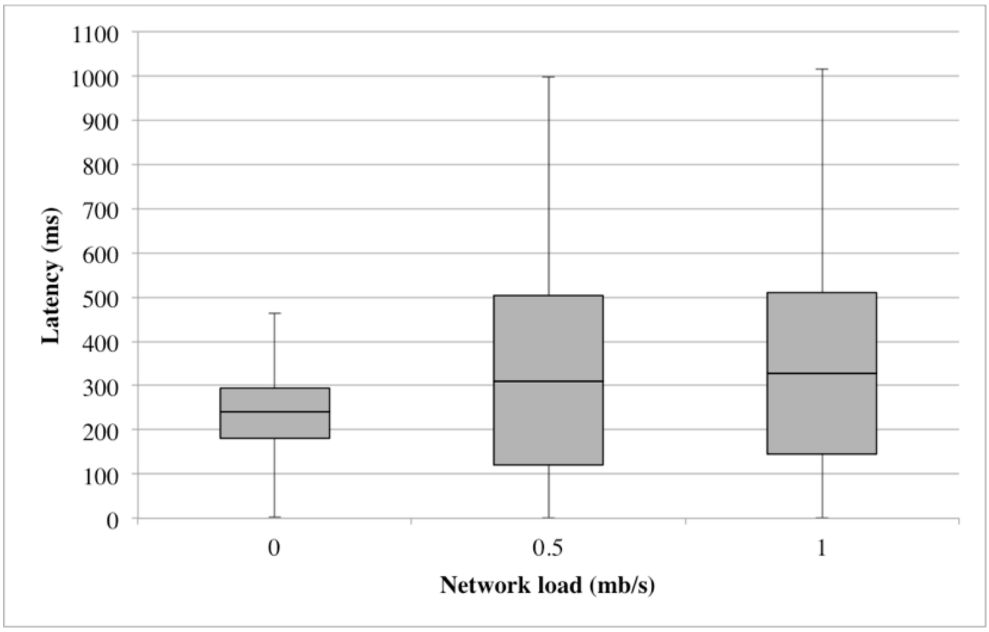

Figure 13. End-to-end latency testing results.

One could criticize the experiment because the test infrastructure was too far away from the actual conditions in data networks. A more complex setup and a wider range of network loads would produce more consistent results; however, they would only represent the latency of the network. The goal of the experiment was to measure the delay introduced by the system, which adds up to the native latency of the network. Based on the results, the use of the telementoring service adds approximately 133.2 ms to the existing latency between the endpoints. This measure enables estimating the video latency of a mentoring session by testing the network before establishing the link. Thus, participants can be notified about the expected disturbances due to the busy networks beforehand.

4.3 RCT1: Studying the usability of telementoring devices and user preferences

Relevant papers: P1, P2, P4

Studied research questions:

Q2: How is mentor response to a mentoring request time influenced by the properties of mentoring hardware?

Q3: Does performing telementoring on different hardware result in comparable outcomes?

The concept of telementoring service becomes a rule changer, as the voided need to attach to the hardware infrastructure enables the employment of ubiquitous devices for remote supervision (Figure 14). The increased availability of clinical expertise escalates the questions of whether the properties of the devices (screen size, mouse/touchscreen input) affect the process of mentoring and the mentor's ability to provide guidance. In other words, is the outcome of telementoring comparable regardless of what device is used on the mentor side?

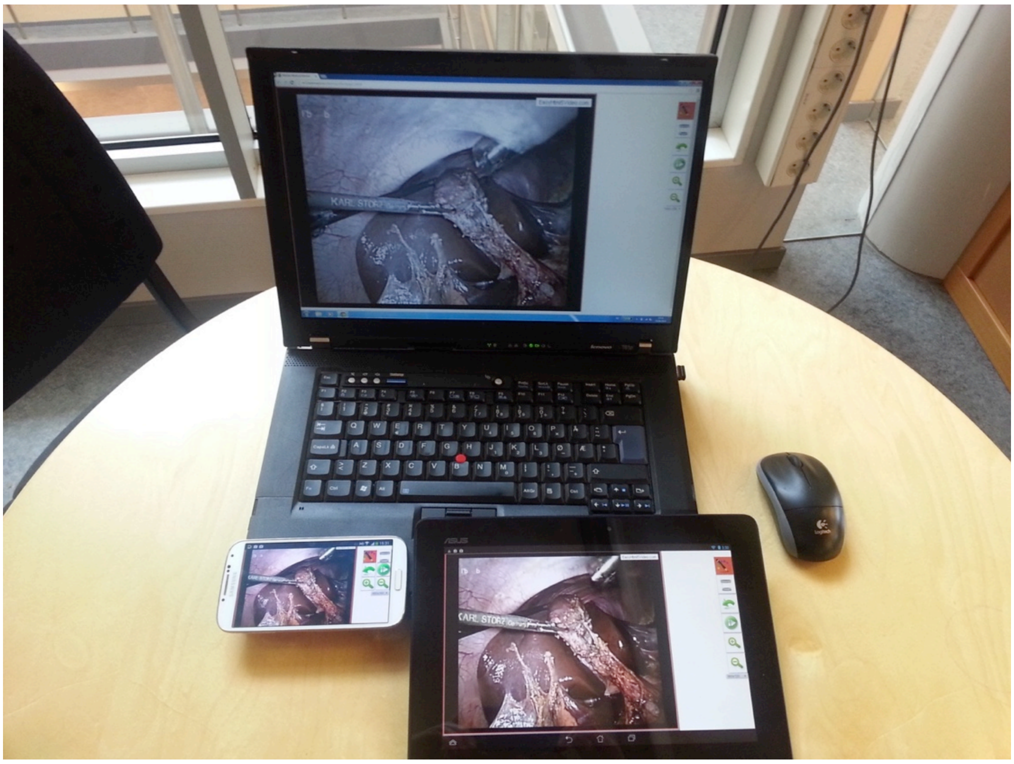

Figure 14. Moments from the trial.

4.3.1 Method

To analyze the behavioral patterns of the mentors switching between different devices, a crossover RCT was designed (Figure 15).

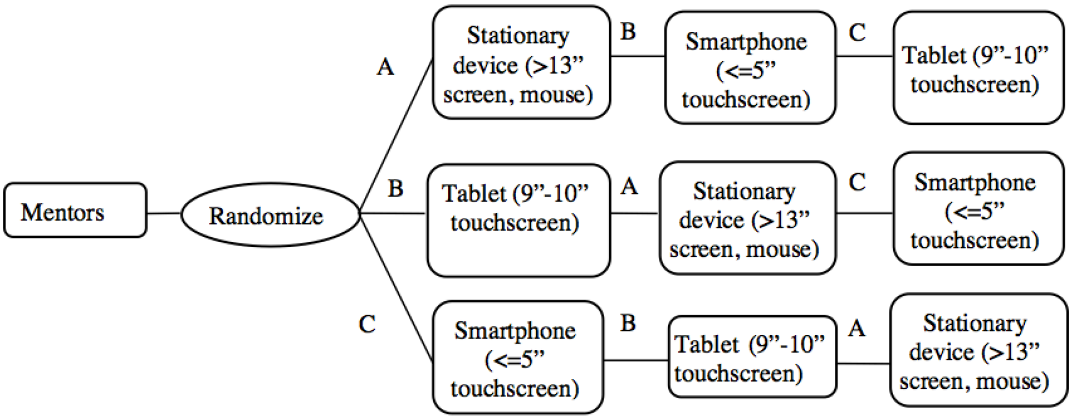

Figure 15. Schematic trial design [11].

Twelve surgeons (age range = 30–62) at the Department of Gastroenterological Surgery (UNN) were recruited to participate in the trial. All of the participants were asked to attend three imitated telementoring sessions using a randomly selected device to perform the same task. A minimum washout period of three days between the devices was set. A laptop computer (Lenovo T61p, 15.4", Core2 duo, 4GB RAM, Windows 7, screen resolution 1920x1200 pixels) represented the stationary platform, an Asus MeMO Pad (10", Full HD, Android 4.2, screen resolution 1280x800 pixels) the medium-sized mobile platform, and a Samsung Galaxy S4 smartphone (5", Android 4.3, screen resolution 1920x1080 pixels) the small-sized mobile platform.

The following measurements were collected and assumptions were questioned in the study [81]:

1. Mentor response time (duration between initiation of mentoring session and the mentor being present online).

   RCT1 H1: Decrease in response time was expected while mentoring on mobile devices (section 1.3, **Q2**).

2. Mentor's interaction with the device (coordinates of annotations and use of pause, resume, and zoom functions).

   RCT1 H2: No significant changes in interaction patterns were expected while switching between mentoring endpoints (section 1.3, **Q3**).

3. Final outcome of mentoring (video and overlaid annotations [80]).

RCT1 H3: No significant changes were expected (section 1.3, **Q3**) [81].

The trial was designed as a non-inferiority study that aimed to prove the absence of significant differences in the mentoring process while switching between the devices.

4.3.2 Results

The results of the study were divided into quantitative (logged automatically) and qualitative (provided by the participants by filling in a questionnaire) categories.

Logging the interactions between the mentor and mentee devices revealed the behavioral patterns of the mentors. The time to react to a mentoring request varied among the platforms (Figure 16, A).

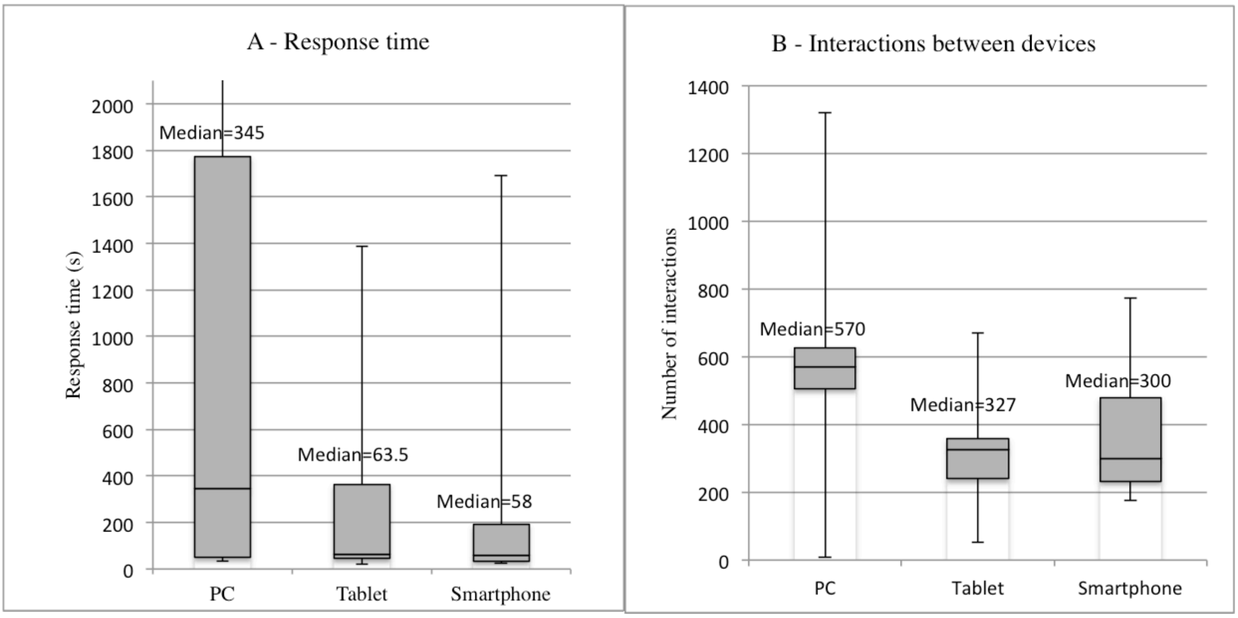

Figure 16. A = response times, B = interactions between mentor and mentee devices per session [81].

The values ranged from 21 seconds to more than 3 hours. The differences between the laptop and the mobile platforms were significant, while the response times between the mobile platforms resulted in insignificant differences (Table 2, row 1).

Different device–device interaction patterns based on the number of interchanged messages (triggered by any move of the cursor while annotating) were observed (Figure 16, B). This provided an outlook on user–device interaction, revealing a higher number of interactions for mouse input than touchscreen for completing the same task. The findings led to analyzing the final products of the sessions – the produced annotations. A high level of detail and accuracy was a typical feature of mouse-produced annotations (Figure 17, A), while touchscreen users were only focused on attracting attention to a certain area without being descriptive (Figure 17, B and C) [81].

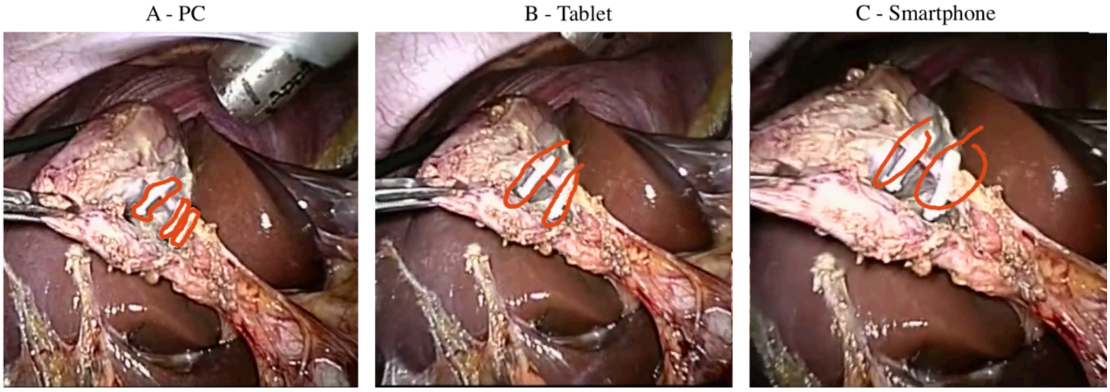

Figure 17. Example of typical annotations produced by A = PC (mouse), B = tablet, C = smartphone [81].

The registered triggering of the “Pause/Resume” functionality did not show any differences among the platforms, whereas the “Zoom” button was clicked slightly more often on mobile devices in comparison to the stationary device. The smaller the screen the telementoring hardware had, the more zooming it required; however, the differences were not statistically significant for either the “Pause/Resume” (Table 2, row 3) or “Zoom” (Table 2, row 4) functions [81].

The mentors’ ability to perceive the video from the laparoscopic camera and annotate it was evaluated via qualitative questionnaire (Appendix 1). Minor differences in ability to identify all visible anatomical structures were reported. The same trend of the smaller screen introducing more challenges was seen. Median measurements demonstrated sufficient identification ability for all platforms (Figure 18, A); the captured differences were statistically insignificant (Table 2, row 5) [81].

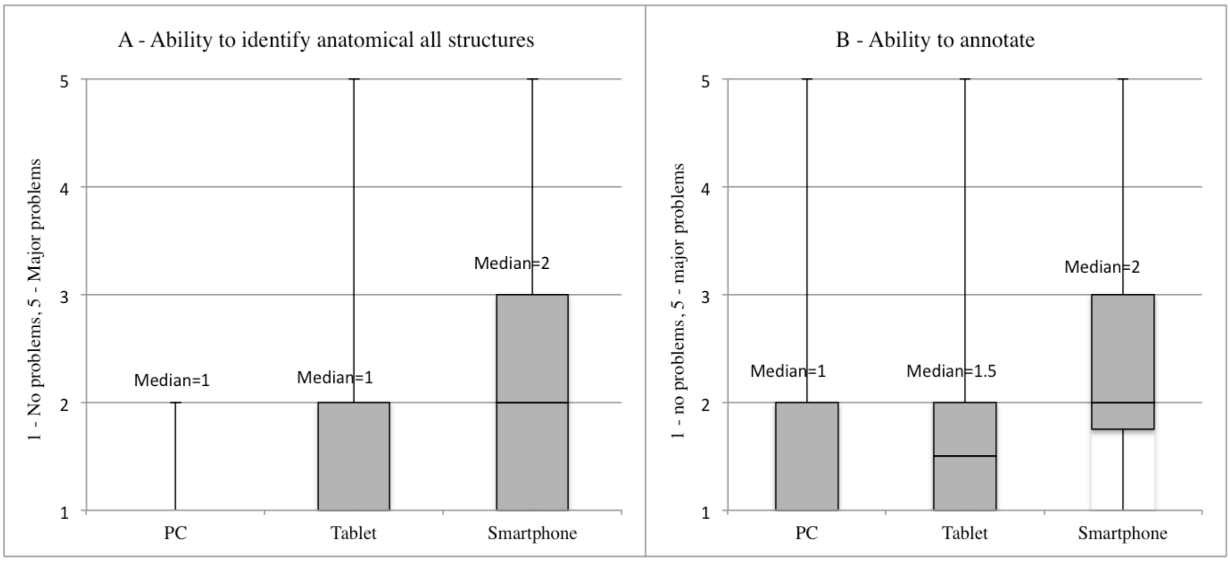

Figure 18. A = ability to identify all anatomical structures, B = Ability to annotate [81].

Annotating the dynamic content introduced more challenges performed on small screen devices (Figure 18, B). In addition to the screen size, laparoscopic camera movement while recording the video increased the complexity of the task. The sufficient accuracy of the annotations (based on the personal evaluation of the participants) was observed for the PC and tablet devices, leaving the smartphone slightly above the threshold (Figure 19, A). The lack of accuracy may be one of the reasons the smartphone was the least-preferred platform for telementoring in the scope of the trial (Figure 19, B) [81].

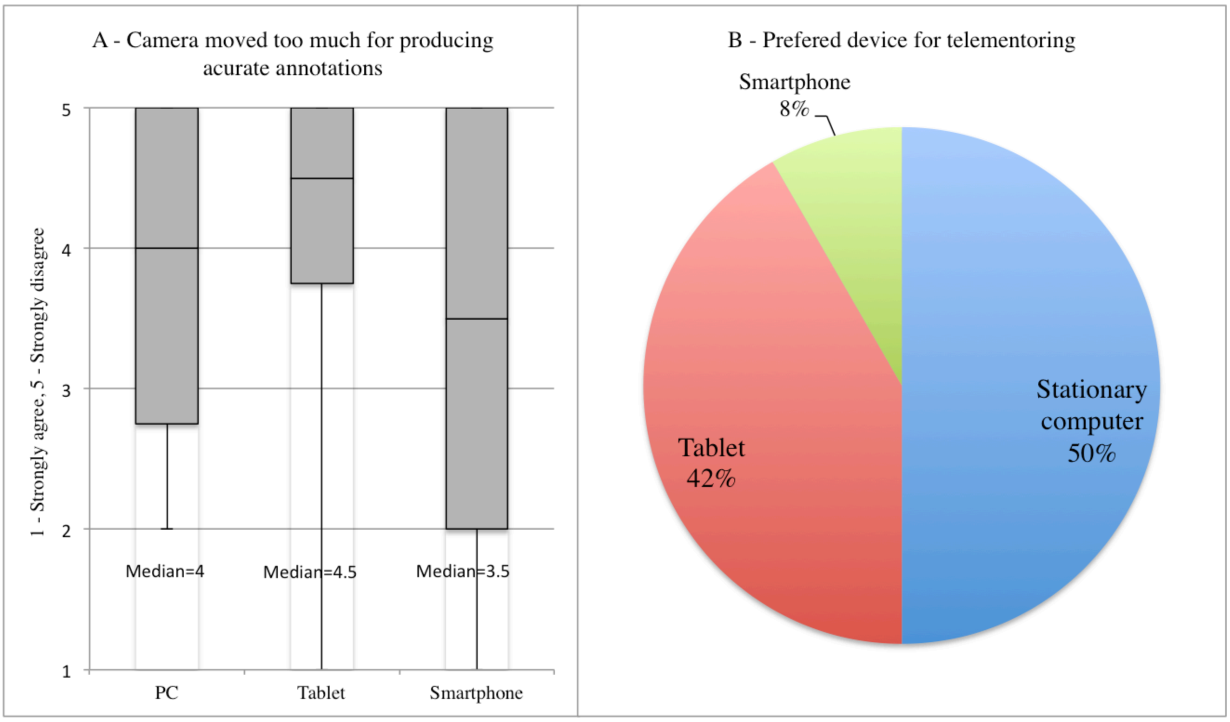

Figure 19. A = Camera moved too much to produce accurate annotations, B = Preferred device [81].

4.3.3 Significance of the findings

P-values and confidence intervals were calculated using the Wilcoxon test for the pairwise measurements (Table 2). The only significant differences among the platforms were in terms of response time and the number of interchanged messages between the devices (values in bold).

Table 2. P-values and confidence intervals (CI) for the comparisons in the trial [81]

No.	Measure	Tablet vs. PC (p-value, CI)	Smartphone vs. PC (p-value, CI)	Tablet vs. smartphone (p-value, CI)
1.	Response time (Figure 16, A)	**.01546, 95%**	.05078, 95%	.6499, 95%
2.	Interactions (Figure 16, B)	**.001953, 95%**	**.01367, 95%**	.4609, 95%
3.	Pause/Resume	.8652, 90%	.8018, 95%	.785, 95%
4.	Zoom	.9666, 95%	.9609, 90%	.3996, 95%
5.	Ability to identify all anatomical structures (Figure 18, A)	.9623, 95%	.9938, 95%	.1325, 95%
6.	Ability to annotate (Figure 18, B)	.6251, 95%	.8559, 95%	.1201, 95%
7.	Camera moved too much to produce accurate annotations (Figure 19, A)	.8016, 95%	.2931, 80%	.8977, 95%

4.3.4 Key findings

The major findings from the trial are summarized below.

1. The trial found that shorter response times occurred when a mobile device was used instead of the stationary device for surgical telementoring. It proves the hypothesis **RCT1 H1** and provides an answer to **Q2**. It is assumed that the response times would differ more in favor of mobile platforms if the experiment were to be performed in real-life settings.
2. No significant changes were observed in the use of the functionality of telementoring service. Regardless of screen size and different inputs, the participants did not show any differences while completing equivalent tasks (**RCT1 H2**, **Q3**).
3. The differences in the interaction patterns were observed while mentors used different devices, resulting in different qualities of the annotations. Comparison of them to claim that one is better than the other may be subjective; therefore, the captured differences were reported. However, associating them with any potential implications of the mentoring outcomes could not be performed (**RCT1 H3**, **Q3**).
4. Regardless of the potential of using a smartphone for handling a mentoring request, it was the least-favored device. Three out of 12 participants claimed that the smartphone was too small for the selected task. However, no major obstacles for not supporting small touchscreen hardware were identified, making the choice dependent on the vision properties of the mentor and his or her experience in using similar hardware.
5. Three out of 12 participants identified the increasing probability of safety-critical implications while telementoring on mobile devices. The major cause was camera instability and potentially inaccurate annotations due to the dynamics of the scene.
6. The department (or hospital) scope is too small to benefit from telementoring. Preplanned device-to-device sessions are resource- and time-demanding on both the mentor's and mentee's sides, considering that supervision by a remote mentor may be required for only a fraction of the procedure. Regional (or national) service resembling a phone-based interaction in terms of the availability of the experts and compatibility of hardware is a good way to explore the potential of telementoring.

4.4 RCT2: Assessing the impact of telestration

Relevant papers: P1, P3, P7

Studied research questions:

Q4: Does the use of telestration while telementoring increase the speed and accuracy of surgical tasks (clinical outcomes)?

Q5: Does the use of telestration while telementoring improve surgical education?

Q6: Does the use of telestration increase the quality of telementoring?

Due to the telestration feature pushing telementoring systems over the threshold to become a medical device [16], the utility of this functionality was researched. The path from the idea to the application in the operating room is time- and resource-consuming in the case of a medical device; however, it is straightforward if the system is used as a communication medium (without telestration) between the mentor and mentee. Assumptions of improving clinical and educational outcomes were verified to determine whether graphical guidance introduces any changes in surgical task completion and learning (Figure 20).

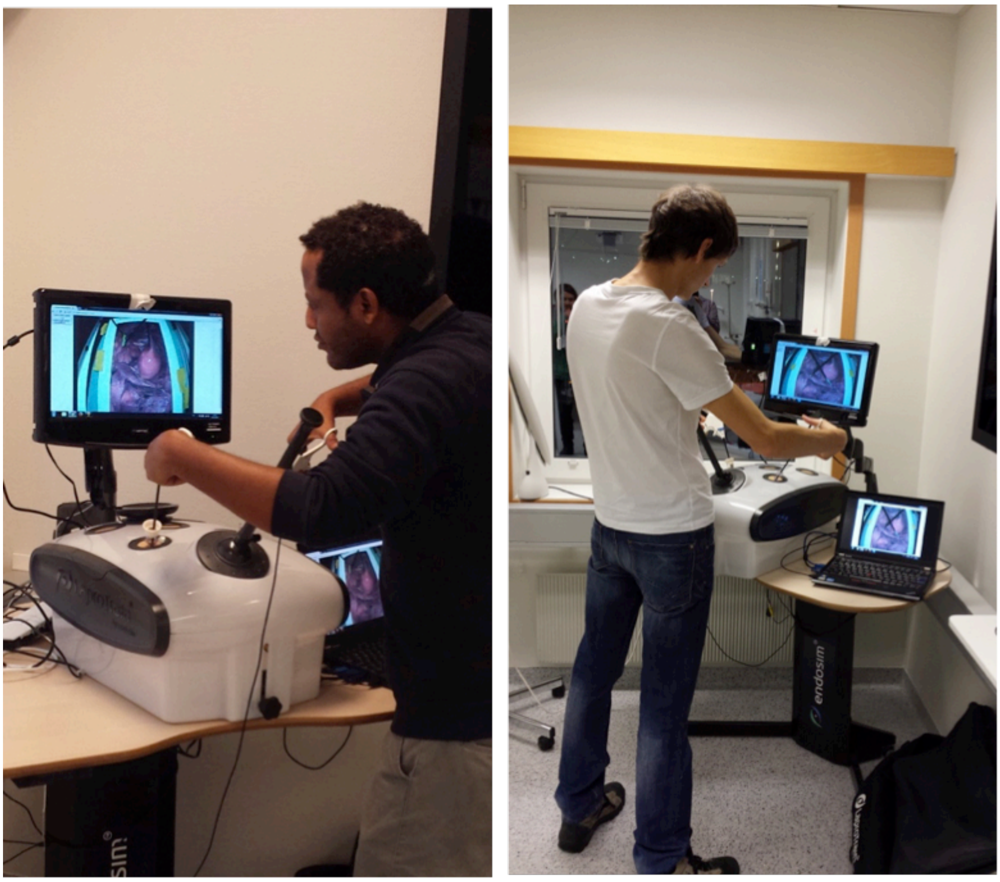

Figure 20. Moments from the trial.

4.4.1 Method

The impact of the telestration feature while mentoring was researched in a crossover RCT. Eight telemedicine and ehealth students at the UiT were remotely mentored while they completed four localization and two cutting tasks using a Laprotrain endoscopic trainer (produced by Endosim[7]) and a paper model of the internal body structure (Appendix 3). Verbal mentoring over VC was put on the control, while telestration supplemented guidance on the intervention arm. The arms were crossed over after the first task without the washout period between the mentoring methods (Figure 21). Memory effects from the first attempt were not considered to bias the results of the second one due to the independency of the tasks.

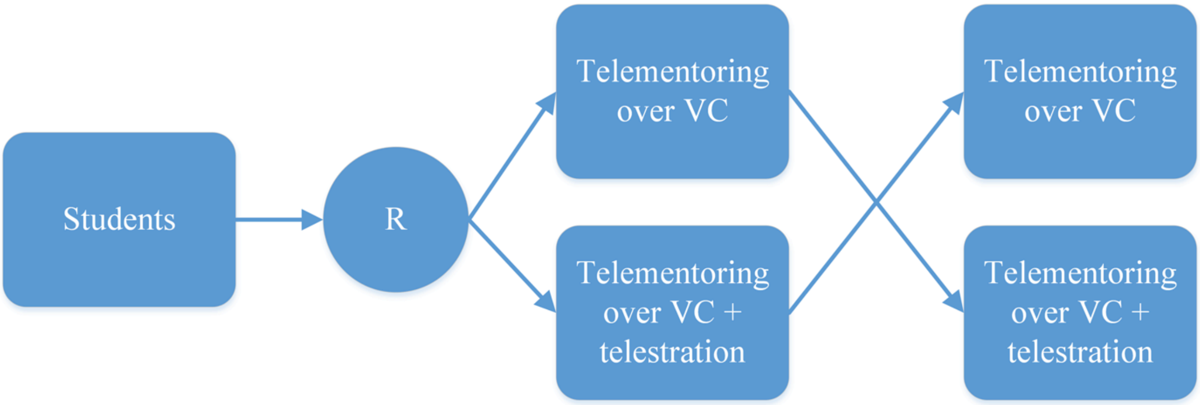

Figure 21. RCT2: Study design [82].

The following measures were collected and the following hypotheses were verified:

1. Clinical benefits (the accuracy of localizing surgical intervention).

   RCT2 H1: At least 10% higher accuracy was expected in the intervention group (section 1.3, **Q4**).

2. Educational benefits.

   RCT2 H2: At least 10% better performance in learning outcomes (repeating the localization task without mentor interference) was expected in the graphically mentored group (section 1.3, **Q5**).

3. Duration of task completion.

   RCT2 H3: At least 10% shorter duration of performing the cut was expected on the intervention arm (section 1.3, **Q4**).

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[7] http://www.laprotrain.com/

4. Quality of mentoring.

   RCT2 H4: At least 10% improvement was expected in the intervention group [62] (section 1.3, **Q6**) [82].

The hypotheses were based on educated guesses supported by the results of an equivalent pilot experiment performed before the trial.

4.4.2 Results

The study revealed no significant differences in localizing the surgical intervention regardless of the mentoring method (Figure 22, A, p-value = .5241, paired T-test). The results were not sufficient to reject the null hypothesis, concluding no significant improvement of clinical outcomes due to the use of telestration to remotely guide the student throughout the procedure. The educational benefits (Figure 22, B), however, favored verbal mentoring. Unexpected differences were observed, refuting the hypothesis of improvement. Telestration while mentoring significantly deterred the accuracy of reidentifying the intervention without guidance (p-value = .0055, paired T-test), revealing that most of the students performed better after being mentored verbally [82].

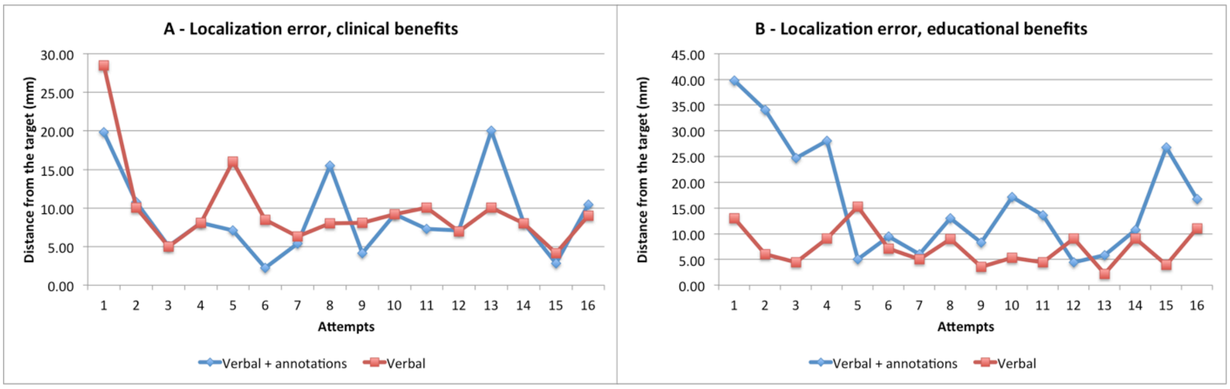

Figure 22. Localization errors in clinical and educational outcomes of telementoring. One participant is represented as two attempts (for example 1 and 2), reflecting the localization of two points for every mentoring method [82].

Verbal mentoring required considerably more time from the mentor and mentee in comparison to graphical guidance (p-value = .0011, paired T-test). Moreover, durations were consistent for all of the participants who were guided graphically, while they varied in the purely verbal scenario (Figure 23A). Two independent raters agreed upon the measures with a squared weighted kappa coefficient of .873 for verbal + annotations and .976 for verbal mentoring methods [82].

Time expenditures to complete the task after the mentoring were guidance method-independent (Figure 23, B). In other words, the durations of the cut were not influenced by the way the students were mentored (p-value = .8544, paired T-test; square weighted kappa = .977) [82].

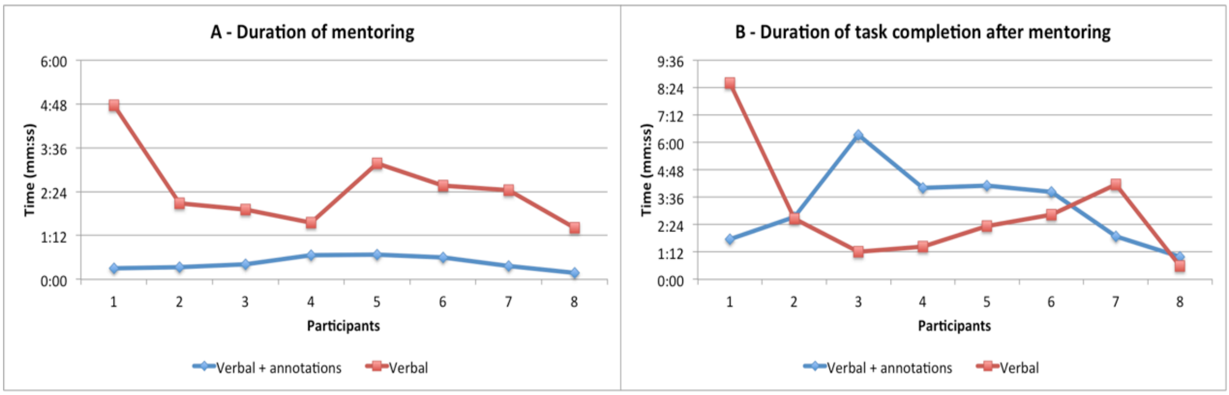

Figure 23. Duration of mentoring and task completion in clinical outcomes [82].

The quality of mentoring was challenging to measure. The raters registered incidents of miscommunication; however, a high level of agreement on the exact number and type of the incidents was not reached. The results are summarized in Table 3, highlighting that the verbal mentoring method introduced more complexity while completing the assigned task (i.e., it lowered the quality of the mentoring). Based solely on the total number of miscommunication incidents, approximately 60% quality improvement was observed for telestration-supplemented mentoring compared to verbal guidance [82].

Table 3. Accuracy of mentoring. The values represent the number of miscommunications between the mentor and mentee as reported by both raters for the analyzed mentoring methods. Equal values (2;2) represent agreement between the raters, whereas positive non-equal values (2;3) represent partial disagreement. Zero and positive values (0;2) represent total disagreement [82]

Participant ID	Verbal + annotations			Verbal		
	Student misunderstood the mentor	Student asked for a clarification	Student needed mentoring after starting the cut	Student misunderstood the mentor	Student asked for a clarification	Student needed mentoring after starting the cut
1	0;0	0;0	0;0	2;2	1;3	1;4
2	0;0	0;0	1;1	0;0	0;0	0;0
3	0;0	**0;1**	**0;1**	0;0	1;1	**0;1**
4	0;0	2;3	2;3	**1;0**	0;0	0;0
5	0;0	0;0	0;0	0;0	**0;1**	1;1
6	0;0	0;0	0;0	2;1	1;1	1;2
7	0;0	0;0	0;0	**1;0**	0;1	1;2
8	0;0	0;0	0;0	**2;0**	0;0	0;0
In total:	0;0	2;4	3;5	8;3	3;7	4;9

4.4.3 Key findings

The major findings from the trial are summarized below.

1. Telestration did not increase the accuracy of localizing the surgical intervention; it was responsible for minor improvements (8.2%), but the expected significance threshold was not reached (**RCT2 H1**, **Q4**).
2. The educational benefits were significantly greater in the verbal mentoring scenario. Most of the participants were more accurate in relocalizing the intervention after being mentored verbally and discussing the specifics of the task with their mentor (**RCT2 H2**, **Q5**).
3. The time required to perform the task was mentoring method-independent. However, if we look at the complete episodes (between when the mentoring began and when the task was completed), an approximately 33% improvement was observed in graphically guided sessions in comparison to verbal ones (**RCT2 H3**, **Q4**).
4. A trend of a higher quality of mentoring was registered in telestrated sessions. Due to ambiguities in the measurements, the exact improvement is difficult to define. Based on the total number of miscommunication incidents during the sessions, approximately 60% higher mentoring quality can be expected from the use of telestration [82] (**RCT2 H3**, **Q6**).
5. Both mentees and mentors supported the use of telestration to minimize the ambiguity in communication when localizing the intervention. Six out of eight students (mentees) reported higher confidence while completing the task under graphical supervision. Seventy-five percent of the participants were in absolute agreement with the mentor guiding them graphically, in comparison to only 25% feeling the same way in the verbal case (results from the qualitative questionnaire, Appendix 2).
6. Both parties discovered an unexpected drawback of telestration. Annotations in the screen transferred the responsibility of performing well to the opposite side of the link: the mentors felt like their work was done after the line appeared on the screen, while students blindly counted on the graphical guidance without questioning it and the cause of the mentors' surgical decisions.

4.5 Summary

Chapter 4 is the concluding block of Friedman's tower of achievements (Figure 2). It summarizes the effects of the contributions presented in previous chapters. In the scope of this PhD project, no real-life effects on patient outcome were analyzed.

The chapter consisted of three studies. Firstly, the validity of the developed system was demonstrated through latency testing, determining the one-way delay introduced by the telementoring service. The measures fell below the reported threshold of 500 ms for having influence on surgical task completion.

Secondly, the usability aspects of telementoring hardware were analyzed, ensuring that the qualities of mentoring were not influenced by the properties of the selected device and input method. The study concluded minor differences in the behavioral patterns of the mentors while using different devices for mentoring. This finding is significant for further development of surgical telementoring services that do not rely on a designated infrastructure.

Finally, the utility of telestration functionality in surgical telementoring scenarios was questioned. The findings revealed a minor improvement in clinical and decline in educational outcomes due to the use of graphical annotations instead of purely verbal supervision over VC. Telestration was, however, responsible for shortening the duration of the mentored episodes and increasing the quality of surgical supervision. The mentors and mentees favored graphically guided sessions to verbal supervision over VC.

5. Conclusions

The conclusions drawn from the experiments are summarized below via mapping the findings to the research questions.

Q1: Do modern web technologies provide a sufficient foundation for developing a surgical telementoring service?

This thesis explored a browser-based VC framework as a foundation for developing clinical services [5]. At the time the experiments were conducted, it was the first attempt to implement a browser-based surgical telementoring system globally.

The selected WebRTC framework [67] provided infrastructure to demonstrate the feasibility of a platform-agnostic telementoring service in non-clinical setups. A latency assessment revealed compliance with the published thresholds for having no influence on surgical task completion [15]. The immaturity of the technology revealed the connectivity challenges in the context of the NHN. Lacking support for the routing mechanisms through secure proxies prevented using the NHN infrastructure in the experiments. The findings identified a weakness of the NHN to support WebRTC-based VC services, connecting the nodes on the different sides of the secure proxy (for example, UNN and the Internet).

The users valued flexibility and availability enhancements. Service-based architecture introduced standardization to the chaotic development of clinical services by providing a VC channel that could be easily integrated into web-based systems. It eliminated the redevelopment of the infrastructure, featured in earlier solutions, as well as minimized maintenance costs in surgical departments aiming to establish telementoring links. It also provided an “off-the-shelf” service for research, enabling easy development of collaboration services without the need to get to the bottom of the technical infrastructure.

Q2: How is mentor response to a mentoring request time influenced by the properties of mentoring hardware?

At the beginning of the project, global interest in using mobile platforms as endpoints for the mentors was minimal. While exploring the potential of ubiquitous devices in the surgical supervision workflow, an assumption of higher availability of the mentors was made, resulting in shorter response time to a mentoring request (which could be of critical importance in emergency cases). The time gains were proven by the results of the RCT1, demonstrating faster response when using a tablet or a smartphone for mentoring in contrast to the stationary computer. Regardless of this important quantitative finding that could potentially shorten procedure duration, the impact on the outcome of the surgery remains unknown.

Q3: Does performing mentoring on different hardware result in comparable outcomes?
The ability to participate in a surgical telementoring session using regular hardware instead of counting on designated devices raised the question of compatibility: How much do the properties of the device (screen size, resolution, input method) influence the mentoring process? The results from RCT1 concluded no significant differences in the use patterns when mentors switched between hardware (apart from the response time) in an imitated mentoring session. This finding strengthens the support for the telementoring service concept, demonstrating the feasibility of hardware-agnostic infrastructure.

Q4: Does the use of telestration while telementoring increase the speed and accuracy of surgical tasks (clinical outcomes)?
The use of graphical annotations to mentor a surgeon speeds up the interaction component of the session. In other words, less time is required to come to a collaborative decision regarding the next step in the procedure. However, no significant difference in the actual task completion was observed. Slightly higher accuracy of localizing the incision was identified in the telestrated sessions. Nevertheless, the differences were not significant, questioning the utility of the telestration functionality.

Q5: Does the use of telestration while telementoring improve surgical education?
The use of telestration in the surgical education scenario revealed deterred progress of the mentee. Verbally mentored students were able to repeat the task with higher accuracy. Both the mentors and the mentees admitted higher focus on the surrounding details and interest in the underlying reasons for the communicated decisions when mentored verbally over VC. It points back to the higher scores in educational outcomes.

Q6: Does the use of telestration increase the quality of telementoring?
Despite the minor improvements in the clinical outcomes and the regression of the educational outcomes, the quality of telementoring was considerably higher in the telestrated sessions. This finding is mostly based on the improvements of the interaction component in the sessions and feedback from the participants, ignoring the quantitative measures of the surgical task completion.

In conclusion, this thesis demonstrated the feasibility of modern web technologies being capable of becoming a foundation for surgical telementoring systems. Comparable mentoring outcomes were demonstrated regardless of the properties of the client-side hardware, enabling telementoring to be performed from the device of the mentor's choice keeping in mind that employing mobile platforms tends to decrease the response time in comparison to stationary platforms. The utility of the highly advertised telestration functionality, bringing the obligations to comply with the restrictive regulatory documents, was demonstrated to be lower than expected for both clinical and educational outcomes. However, the increased quality of the mentor–mentee interaction component in the telementoring sessions and the positive feedback from the participants encourages supporting the feature as part of surgical telementoring functionality.

The thesis demonstrated contributions to each level of Friedman's tower of achievements in medical informatics (Figure 2). Technical challenges and changes in regulatory frames prevented integration of the telementoring service into daily clinical practices and assessing its utility in surgical procedures in the operating room in the scope of this PhD project. Regardless the partial contributions to "System installation" and "Study of effects", covering all levels of the tower of achievements show the completeness of this thesis.

6. Limitations

The combination of the safety-critical scenario and international regulations [16], [17] limited the experiments to a number of test setups instead of the actual clinical assessment, which is the main limitation of the findings. The demo environments were tailored to resemble the actual deployments; however, the attitude of the participants may have been biased by the selected approach. Participation in the trial had to compete with participants' regular duties in the surgical department in RCT1, setting a lower priority for the study. It is likely that mentoring an actual case would deliver more representative results; however, dramatic differences in the observed trends are not expected.

Case dependency cannot be denied. Both RCTs used videos and images recorded during a regular laparoscopic procedure at UNN. Due to the varying complexity of the case, fluctuations in the observed measures were expected. The trials were targeting a procedure of average complexity to provide quantitative estimates. The reported results may need to be adjusted to encompass either extremely difficult or extremely easy scenarios.

Sample size is another weakness of both RCTs, making the results balance between proof and demonstration of effect. The use of language in the trials may have influenced the performance of non-native English speakers and may have introduced additional bias. Further studies are planned to add more subjects and provide solid evidence supporting the findings.

The technological literacy of the participants and awareness of the telemedical techniques may have shaped the qualitative results of the study. VC is highly utilized in many care-over-distance techniques at UNN, possibly resulting in a more optimistic evaluation of the proposed solution.

The mentioned limitations may question the validity of the results. The demonstrated findings need to be strengthened by performing larger studies in more realistic scenarios to reach unquestionable conclusions.

7. Directions for future work

This PhD project produced at least two artifacts calling for further exploration: the general purpose VC service will be integrated into more telemedical projects, and clinical evaluation is a long-term goal for the telementoring system.

7.1 Telementoring service

Future work, from the point of functionality, mainly concerns the extensions for multi-party telementoring. The current version supports a one-to-one mentor–mentee VC link; however, team-based supervision is already being discussed. The extensions will bring the annotations originating from any connected party into existence (an upgrade to the current mentor–mentee annotations). The feasibility and benefits of having multiple mentors needs to be evaluated.

Upgrades are planned for the telestration toolbox to compensate for the inaccuracy of the annotations caused by the moving camera. The identified threat to patient safety due to misplaced annotations has to be handled before beginning experiments in more realistic scenarios. The trials supported the importance of handling potential miscommunications between the mentor and mentee occurring due to poor distinction of features when annotating the dynamic videos. The camera movement problem and potential solutions have already been discussed, leaving the implementation and evaluation for further research [48], [83].

Following the international regulations [16], [17], approval of the telementoring service as a medical device is planned for the future. The performed experiments partly cover the required non-clinical testing [52]. Additional experiments are required to have sufficient proof that allows for the progression to clinical studies.

The studies supported the claims of the potential of telementoring; however, changes in the deployment scale are suggested to fully exploit them [81]. A shift from a research project to a regional/national service that brings surgeons together for telementoring-based collaboration is required if it is to become a common clinical practice. The ideas look rather straightforward in theory; however, a number of constraints hinder their actual implementation. Hands-on experience with the deployment of the service at UNN revealed the networking barriers limiting the progress of VC-based services connecting the hospital with the Internet. Administrative changes, making sure the mentors have designated time for mentoring, and legal questions about responsibility for the mentoring process are just a couple of future research topics.

The role of the mentor in telementoring scenarios needs to be explored. By means of a telementoring system, a remote expert becomes a part of the surgical team in the operating room. However, understanding of the collaboration in distributed surgical teams is still limited [32]. Differences in work practices, trust management, and division of responsibilities are just a few questions that call for further investigation.

7.2 Reuse of the general purpose VC service

The research project proposed a generic architecture for developing VC-based clinical services [5]. The prototypical implementation demonstrated the feasibility of the solution, delivering the foundation for telementoring and VC-based doctor–patient consultation projects[8].

The infrastructure has already attracted the attention of the researchers at NST and is under consideration to provide VC capabilities for other projects. The expansion of the currently available basic functionality is planned to offer a full-blown VC gateway for clinical services, enabling easy integration and reuse without spending resources on low-level technical problems. Supporting the collaborators with the integrated research tools for analyzing the interactions via developed services is one of the main focuses of the initiative.

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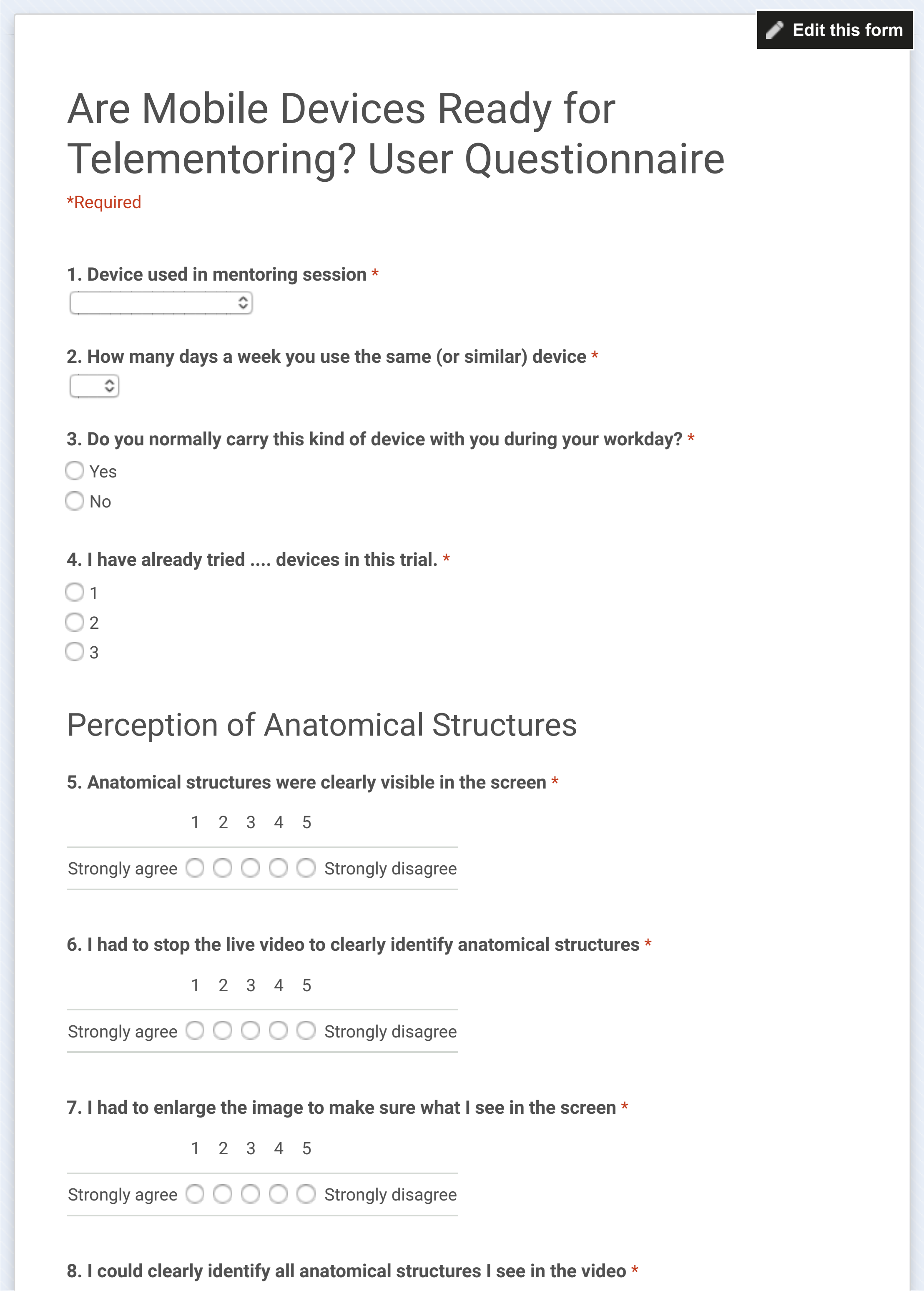
[8] Explored by Timotheus Kampik, a master student at UiT under the supervision of Prof. Johan Gustav Bellika and PhD candidate Andrius Budrionis.

8. Appendixes

Appendix 1. RCT1 participant questionnaire



Are Mobile Devices Ready for Telementoring? User Questionnaire

*Required

1. Device used in mentoring session *

2. How many days a week you use the same (or similar) device *

3. Do you normally carry this kind of device with you during your workday? *

○ Yes
○ No

4. I have already tried .... devices in this trial. *

○ 1
○ 2
○ 3

Perception of Anatomical Structures

5. Anatomical structures were clearly visible in the screen *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

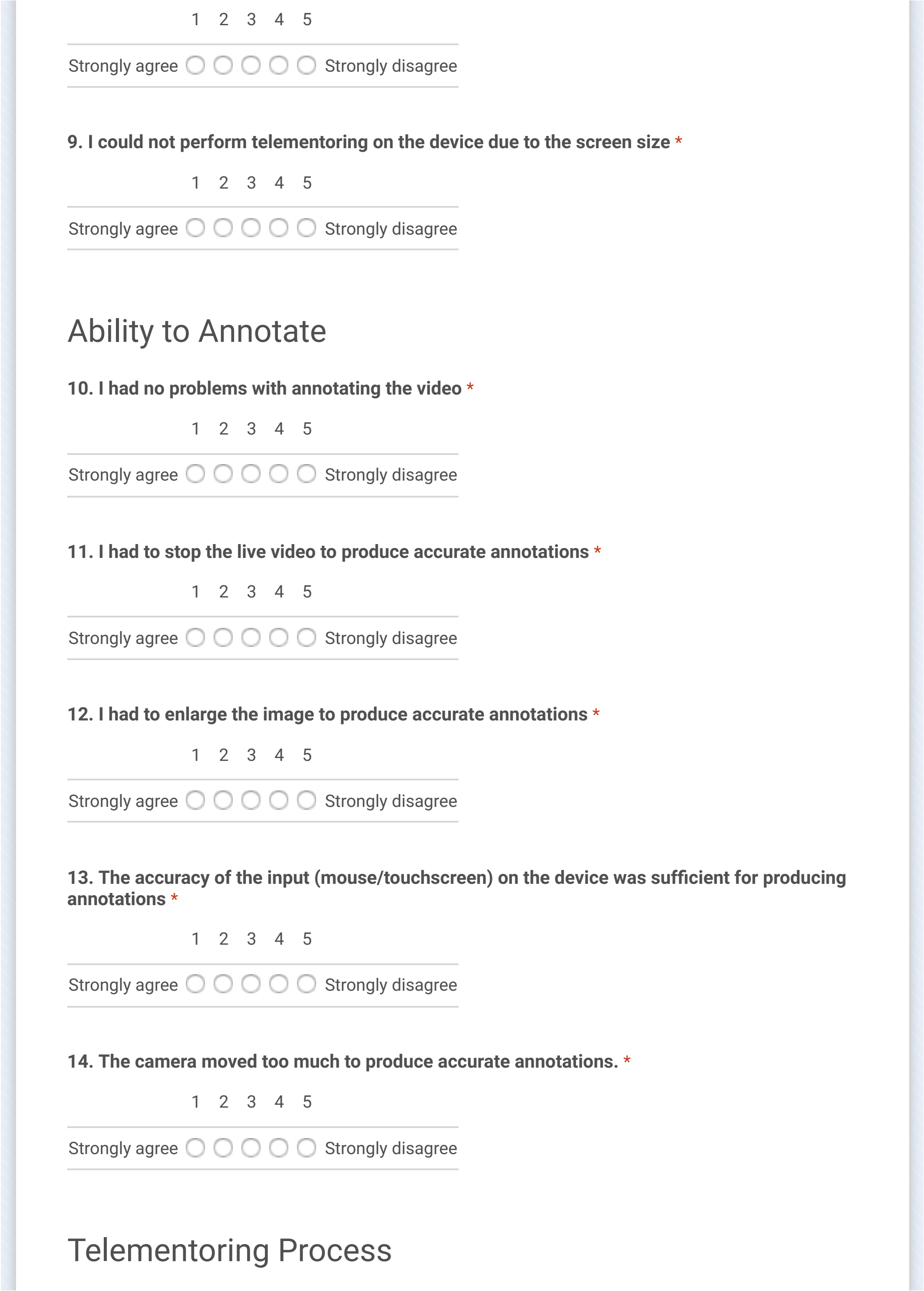
6. I had to stop the live video to clearly identify anatomical structures *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

7. I had to enlarge the image to make sure what I see in the screen *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

8. I could clearly identify all anatomical structures I see in the video *



	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

9. I could not perform telementoring on the device due to the screen size *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

Ability to Annotate

10. I had no problems with annotating the video *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

11. I had to stop the live video to produce accurate annotations *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

12. I had to enlarge the image to produce accurate annotations *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

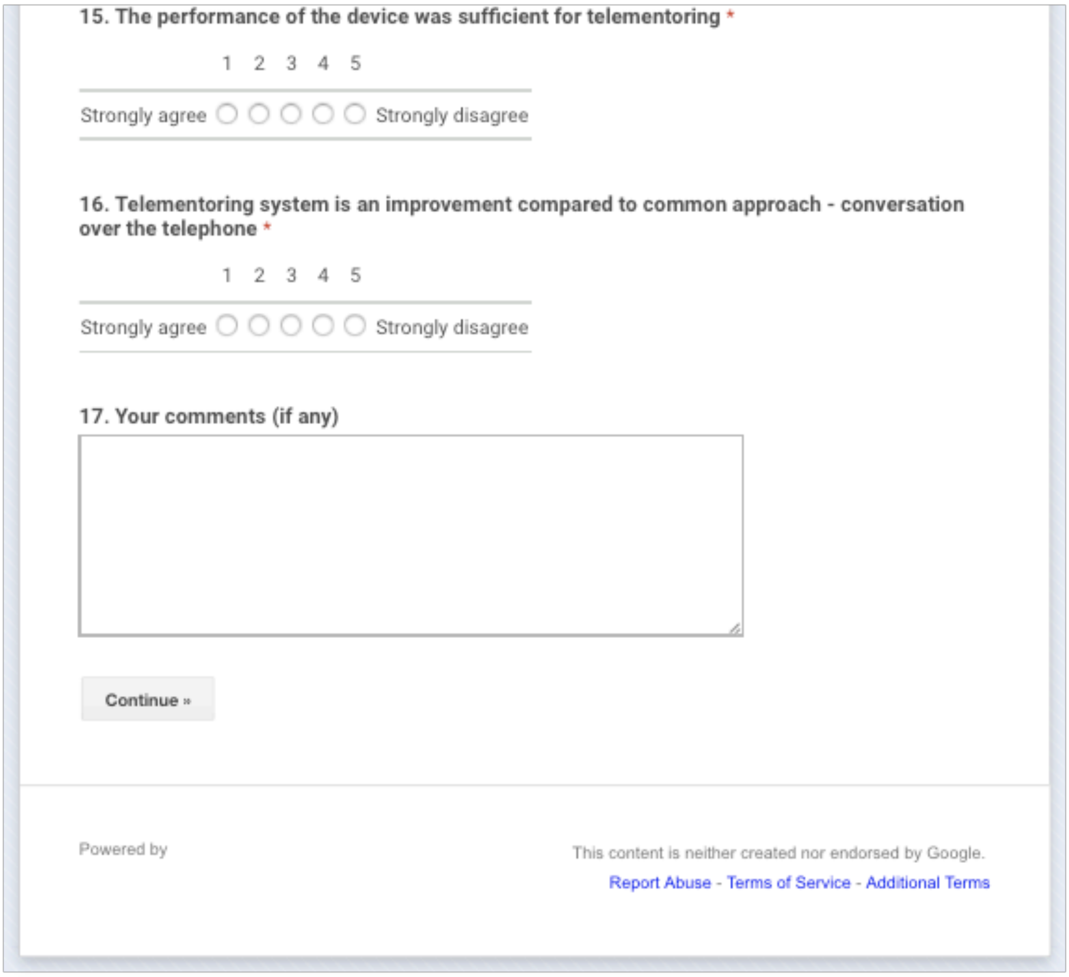
13. The accuracy of the input (mouse/touchscreen) on the device was sufficient for producing annotations *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

14. The camera moved too much to produce accurate annotations. *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

Telementoring Process



15. The performance of the device was sufficient for telementoring *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

16. Telementoring system is an improvement compared to common approach - conversation over the telephone *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

17. Your comments (if any)

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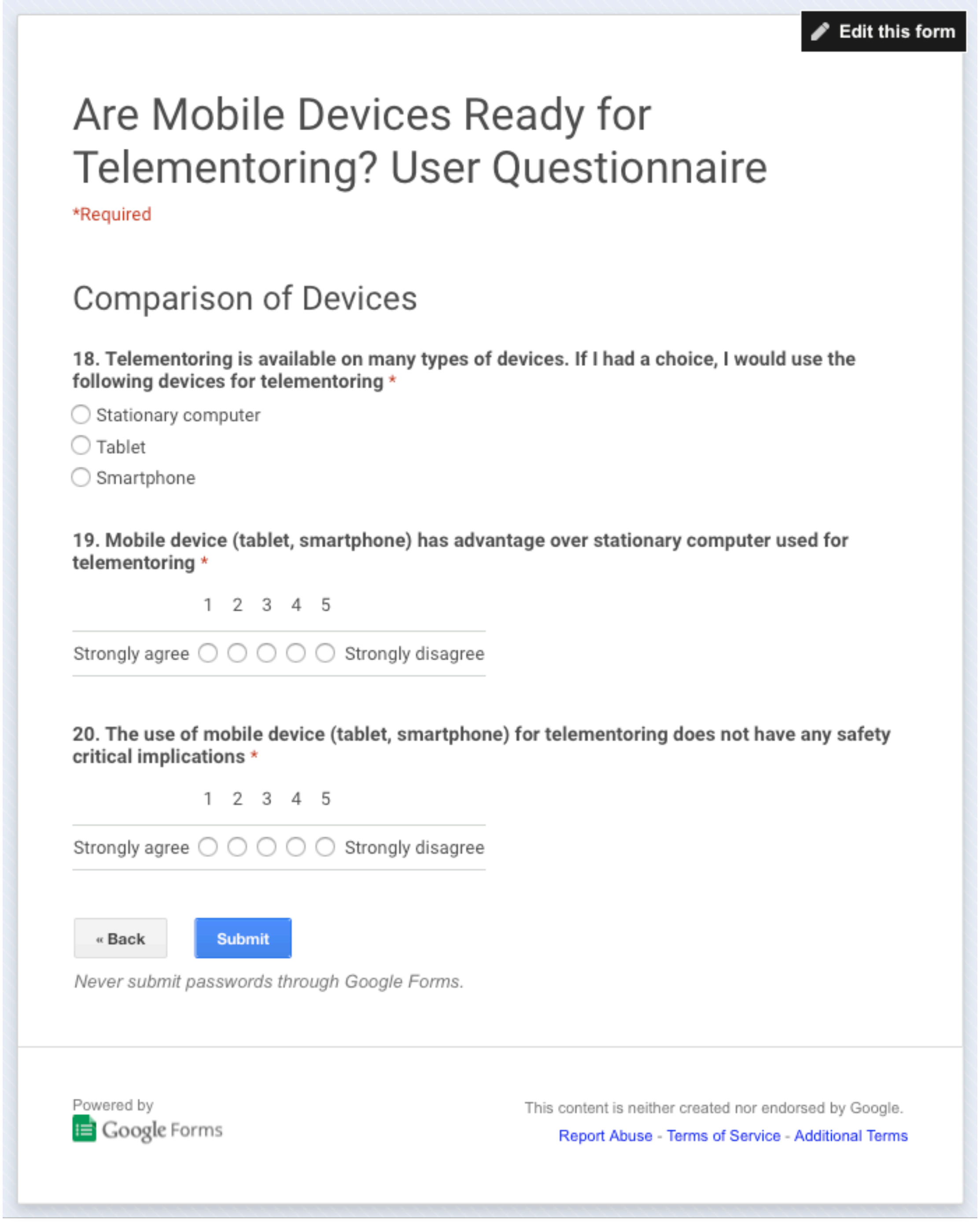

Are Mobile Devices Ready for Telementoring? User Questionnaire

*Required

Comparison of Devices

18. Telementoring is available on many types of devices. If I had a choice, I would use the following devices for telementoring *

○ Stationary computer
○ Tablet
○ Smartphone

19. Mobile device (tablet, smartphone) has advantage over stationary computer used for telementoring *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

20. The use of mobile device (tablet, smartphone) for telementoring does not have any safety critical implications *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

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Appendix 2. RCT2 participant questionnaire

NST
Norwegian Centre for
Integrated Care and Telemedicine

Norwegian Centre for Integrated Care and Telemedicine
P.O. Box 35
N-9038 Tromsø
NORWAY
Telephone (+47) 07766
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info@telemed.no

Understanding the benefits of telestration in telementoring
Randomized Controlled Trial

Participant questionnaire

You have just completed a training task while being guided by a remote mentor. The task was twofold – you were either guided verbally or verbally and graphically (annotations on the screen). Please reflect your experiences on the mentoring methods by selecting **one** answer to every question.

1. Which method of telementoring did you prefer?
   a) Verbal guidance
   b) Verbal and graphical guidance
   c) Both
   d) None

2. Do you think the graphical guidance helped you to perform more accurately?
   a) Yes
   b) No
   c) I am not sure

3. Did you feel more confident in completing the task while being mentored by graphical annotations in comparison to verbal instructions?
   a) Yes
   b) No
   c) I am not sure

4. Did the graphical guidance allow you to focus more on the training task, not emphasizing the localization of a particular structure?
   1. Yes
   2. No
   3. I am not sure

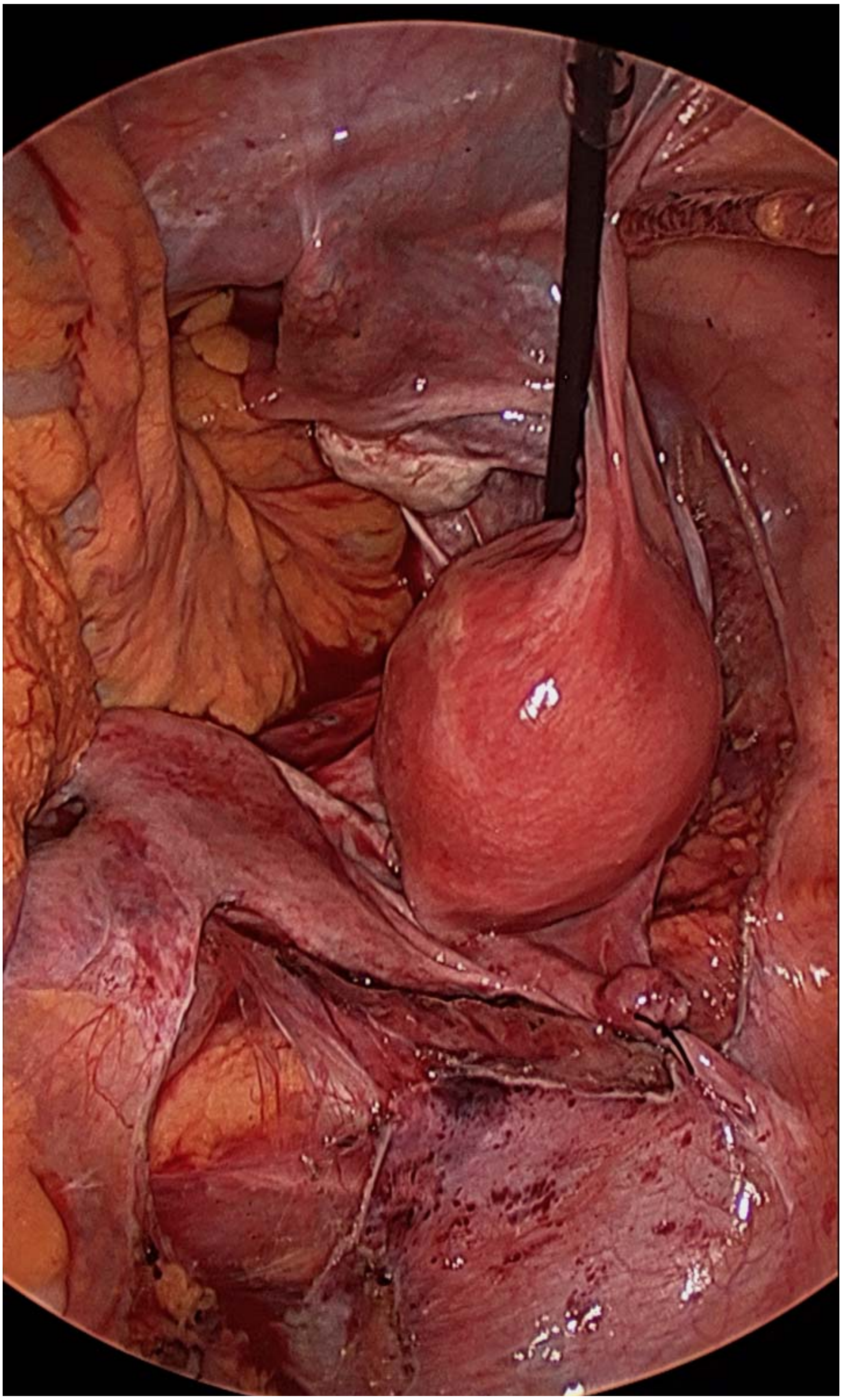
5. Did you feel you were doing **exactly** what the mentor was asking you to do while mentored:
   5.1. verbally?
      a) Yes
      b) Most of the time
      c) Sometimes
      d) I am not sure

   5.2. verbally and graphically?
      a) Yes
      b) Most of the time
      c) Sometimes
      d) I am not sure

6. Please flip the sheet over and mark the incisions you have made using the simulator in the figure.

Thank you for your contribution!

Appendix 3. RCT2 paper model



Appendix 4. Report of the systematic literature review on telementoring applications

	Keywords	# of results	Rejected as duplicates	Rejected by title or abstract	Included	Included
	Pubmed					
	2000 - 2015					
Q1	telestration or annotation and telementoring	8		4	4	A novel interface for the telementoring of robotic surgery. Novel telementoring system for robot-assisted radical prostatectomy: impact on the learning curve. Tracking of irregular graphical structures for tissue deformation recovery in minimally invasive surgery. The RoboConsultant: telementoring and remote presence in the operating room during minimally invasive urologic surgeries using a novel mobile robotic interface.
Q2	telestration or annotation and teleproctoring	0			0	
Q3	telestration or annotation and surgery	43	5	37	1	3-D telestration: a teaching tool for robotic surgery.
Q4	telestration or annotation and conferencing	4		3	1	Robotic telementoring/telesurgical system and randomized evaluation study.
Q5	telementoring or teleproctoring and web	6	2	2	2	Surgical Trainee Opinions in the United Kingdom Regarding a Three-Dimensional Virtual Mentoring Environment (MentorSL) in Second Life: Pilot Study. The "tele" factor in surgery today and tomorrow: implications for surgical training and education.
	IEEExplore					
Q1	telestration or annotation and telementoring	3	1		2	An augmented reality approach to surgical telementoring Remote telesurgical mentoring: feasibility and efficacy
Q2	telestration or annotation and teleproctoring	0			0	
Q3	telestration or annotation and surgery	20	3	16	1	Interactive visual content sharing and telestration: A novel network multimedia service
Q4	telestration or annotation and conferencing	12	1	8	3	Improving co-presence with augmented visual communication cues for sharing experience through video conference Study of augmented gesture communication cues and view sharing in remote collaboration Comparing pointing and drawing for remote collaboration
Q5	telementoring or teleproctoring and web	2			2	Telementoring in surgery in East Coast Design and implementation of a collaborative virtual haptic surgical training system
	ACM					
Q1	telestration or annotation and telementoring	3		2	1	Exploring the social-technological gap in telesurgery: collaboration within distributed or teams
Q2	telestration or annotation and teleproctoring	1	1		0	
Q3	telestration or annotation and surgery	5		4	1	Annotation of endoscopic videos on mobile devices: a bottom-up approach
Q4	telestration or annotation and conferencing	3		2	1	World-stabilized annotations and virtual scene navigation for remote collaboration
Q5	telementoring or teleproctoring and web	13	2	10	1	A low cost digital operating room
	In total	123	15	88	20	

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10. Included research papers