Pedagogical Approaches for Surgical Education

Éléonore Barbut Ferrier-Barbut

THÈSE

présentée pour obtenir

le titre de docteur délivré par Sorbonne Université

École doctorale: Science Mécanique, Acoustique, Électronique et Robotique de Paris

par

Eléonore FERRIER-BARBUT

Pedagogical Approaches for Surgical Learning

Pierre JANNIN	Directeur de recherche INSERM	President du jury
Jocelyne TROCCAZ	Directrice de Recherche CNRS -HDR	Rapporteuse
Elise LAVOUE	Maître de conférences -HDR	Rapporteuse
Gilles BAILLY	Chargé de recherche CNRS	Examinateur
Geoffroy CANLORBE	Professeur des universités - Pracitien Hospitalier	Invité
Françoise WAQUET	Directrice de Recherche émérite au CNRS	Invitée
Marie-Aude VITRANI	Maîtresse de Conférences à Sorbonne Université	Directrice de thèse
Vanda LUENGO	Professeure des Universités à Sorbonne Université	Co-Directrice de thèse

Institut des Systèmes Intelligents et de Robotique (ISIR)
Pyramide Tour 55, 4 place Jussieu
UMR CNRS 7222, Paris, France

Résumé

Les étudiants et étudiantes en médecine rencontrent de nombreuses difficultés dans leur apprentissage de la chirurgie, difficultés qui ont pour conséquence l'abandon de cette spécialité pour un grand nombre d'entre eux et elles. Ces difficultés sont dues principalement à la diminution des heures passées au bloc opératoire, à apprendre en observant et en faisant. Pour pallier à ces difficultés, il existe aujourd'hui de nombreux dispositifs de simulation qui permettent aux chirugiens et chirurgiennes en apprentissage de s'exercer hors du bloc opératoire, dans des conditions moins stressantes, et de manière répétée. Cependant, ces dispositifs, aussi nombreux et variés soient-ils, échouent à couvrir efficacement l'ensemble des multiples connaissances et compétences nécessaire à l'apprentissage de la chirurgie. Le spectre de ces connaissances et compétences est large, du technique (dextérité, connaissances en anatomie, risques, instruments, étapes des interventions etc.) au non-technique (conscience de la situation, capacité à formuler un plan d'action, à rassembler des informations, à diriger une équipe etc.). Une des principales raison à ce manquement, est dûe au fait que ces dispositifs, bien souvent de haute technologie, ne sont pas conçus sur la base de considérations pédagogiques, ou sur l'apprentissage humain en général, et l'apprentissage de la chirurgie en particulier. En effet, les considérations sont souvent plutôt technologiques que pédagogiques. Cette thèse vise donc, d'abord, à décrire de manière aussi exhaustive que possible, l'ensemble des connaissances et compétences nécessaires à la maîtrise de la chirurgie. Ensuite, la thèse vise à définir l'impact de différents dispositifs d'entraînement à la chirurgie, dont la conception aura été guidée par des considérations pédagogiques, sur l'évolution de ces compétences, en comparaison avec des dispositifs d'entraînement plus classiques -et donc moins pédagogiques. Les résultats démontrent qu'une approche pédagogique dans la conception de dispositifs technologiques d'entraînement pour la chirurgie peuvent permettrent de participer au développement des compétences cibles (*i.e.* à l'oeuvre lors de performance en conditions réelles), au développement de connaissances indispensables à la réalisation du geste et difficilement accessibles et démontrent une tendance à l'augmentation des compétences techniques en conditions réelles.

Key Words: Apprentissage humain, Education en Chirurgie, Design Centré Utilisateur

Abstract

Medical students face many difficulties in learning surgery, which result in many of them abandoning the specialty. These difficulties are mainly due to the decrease in hours spent in the operating room, learning by watching and doing. To overcome these difficulties, there are now many simulation devices that allow surgeons in training to practice outside the operating room, in less stressful conditions, and in a repeated manner. However, these devices, as numerous and varied as they are, fail to effectively cover all of the multiple knowledge and skills necessary to learn surgery. The spectrum of this knowledge and skill is wide, from the technical (dexterity, knowledge of anatomy, risks, instruments, steps of the procedures etc.) to the non-technical (situational awareness, ability to formulate a plan of action, gather information, lead a team etc.). One of the main reasons for this is that these devices, often high-tech, are not designed on the basis of pedagogical considerations, or on human learning in general, and surgical learning in particular. Indeed, the considerations are often more technological than pedagogical. This thesis therefore aims, first, to describe as comprehensively as possible, the body of knowledge and skills necessary to master surgery. Then, the thesis aims to define the impact of different surgical training devices, whose design will have been guided by pedagogical considerations, on the evolution of these skills, in comparison with more classical - and therefore less pedagogical - training devices. The results show that a pedagogical approach in the design of technological training devices for surgery can participate in the development of target skills (i.e. those used during performance in real conditions), in the development of knowledge that is essential to the realization of the gesture and difficult to access, and demonstrate a tendency to increase technical skills in real conditions.

Key Words: Human learning, Surgical education, Human-centered design

Remerciments

Je tiens d'abord à remercier mes encadrantes, Marie-Aude et Vanda qui par leurs conseils bienveillants et par la confiance qu'elles m'ont conférée tout au long de la thèse, m'ont permis de mener cette aventure au bout. Marie-Aude, merci d'avoir été là pour répondre à mes questionnements, et pour avoir toujours su trouver les mots qui m'ont permis d'avancer, mais aussi d'oser explorer des questionnements scientifiques très différents de ceux traditionnellement explorés à l'ISIR. Vanda, merci pour toutes les connaissances que tu m'as transmises et qui m'ont menée jusqu'au coeur de la problématique de la thèse. Merci aussi d'avoir toujours poussé un peu plus loin les exigences, qui ont permis à mon travail de gagner en qualité. Merci à tou-te-s les membres du jury, qui ont chacune et chacun apporté un éclairage important sur le travail effectué pendant la thèse, et dont les questionnements soulevés vont encore me porter pendant longtemps. Je les remercie beaucoup d'avoir pris le temps de lire ce manuscrit. Merci tout particulièrement à Geoffroy : sans ton enthousiasme, sans ton accueil inconditionnel au bloc opératoire (ainsi que celui de tout-e-s les membres de ton service), sans la mise en relation que tu as permise avec les internes, avec tes collègues chirurgiennes et chirurgiens, sans la présence continue dont tu as fait preuve tout au long de la thèse, je n'aurai obtenu aucun des résultats présentés dans cette thèse et je ne serai pas non plus allée aussi loin dans les questionnements qui me tiennent à coeur aujourd'hui.

Merci aussi à tou-te-s les personnels administratifs et techniques : Michèle, Sylvie, Awatef, Adela, Anne-Claire, Yves, qui savent toujours être humain-e-s et à l'écoute, et bien sûr Philippe et David qui ont permis la réalisation des différentes expériences de la thèse, et avec qui j'ai toujours eu beaucoup de plaisir à travailler, mais aussi à échanger en dehors du travail. Un grand merci à Lolo pour son humanité sans limites, mais aussi et surtout pour le magnifique arbre de vie que je garderai, précisément, toute ma vie et plus. Merci aussi à Flo, pour ta disponibilité et ta bonne humeur à toute épreuve.

Je remercie bien sûr, du fond du coeur, toute l'équipe Agathe qui a partagé avec moi si ce n'est tous les jours de cette thèse, en tout cas une immense partie. Merci à Angélina, Mario, Mathilde, Omar et Rémi d'avoir été des présences rassurantes, les plus "grands". Vous êtes des exemples de dévouement pour le travail et d'implication pour la vie de l'équipe. Merci à Mégane, Jésus, Jimmy, et Josh avec qui j'ai partagé le J05 toutes ces années : vous avez supporté mes rires mais aussi mes pleurs et mes doutes. Je n'oublierai jamais aucun de nos moments passés ensemble -tout particulièrement ceux, où, lorsque nous étions tous ensemble dans le bureau, nous avions tant de choses à nous dire que nous n'arrivions pas à travailler... Un merci particulier à Etienne également, pour tous les moments d' "écoles d'été et d'hiver", pour les conseils, pour les discussions, pour les interprétations de Garou et Céline. Merci à Félix, Clémence, Charlotte, Alexis, Antoine, Delphine et aux "nouveaux" : Ousmane, Solène, Océane, Lylian, Guillaume S., Saman j'espère pouvoir dire que j'ai lié avec vous une amitié et que nous nous reverrons à Savonnières, ou bien dans le Jura. L'écoute bienveillante et le soutien qui sont les mots d'ordre de cette équipe et qui vont continuer de l'être, je suis sûre, sont le fruit de chacun de vous, de ce que vous apportez et c'est une chance incroyable d'avoir cela quand on est doctorante.

Un grand merci également aux permanents, Ludo, Fabien, Nath, Emmanuel, Wael, Jérôme qui connaissent la difficulté de faire des manips, de rédiger des articles, de mener à bien des protocoles expérimentaux et qui savent toujours veiller sur nous. Merci aussi à Guillaume M., pour m'avoir encouragée dans la création de liens avec des chercheuses et chercheurs en sciences humaines et sociales, chaque rencontre m'a ramenée à mes racines de "philosophe" et a été pour moi un tournant dans la thèse. Un très grand merci à Ignacio, autant professionnellement que personnellement, la générosité dont tu es capable de faire preuve, les coups de mains que tu es capable de donner, m'ont énormément aidée. Et ce d'autant plus que tu connais parfaitement le bloc opératoire, mais aussi les techniques en sciences humaines et sociales.

Merci à mes amies "de Paris" et "de Grenoble" : Romane, Lina, Julie, Lucie, Camille, Adélie, Morgane, vous êtes chacune des présences indispensables à mes côtés, et je me sens très privilégiée et fière de partager des moments avec vous, qui êtes tellement inspirantes, mais aussi -il faut le dire- très drôles, et ça n'est pas de trop lorsqu'on fait une thèse.

Evidemment, merci à ma famille proche : mon frère et ma soeur, sans vous, sans votre sagesse, sans votre connaissance du milieu de la recherche, tout aurait été tellement plus difficile. Depuis toujours vous êtes des exemples, des soutiens. Merci à mes parents; à ma maman pour m'avoir encouragée dans mes décisions, pour ton courage face aux difficultés de la vie, pour ton amour de la nature et des autres qui m'inspire tant; à mon papa, nous n'avons pas passé beaucoup d'années ensemble et pourtant je m'en souviens encore et elles ont suffit à me porter jusqu'ici, c'est dire l'intensité de ton amour pour nous, pour la vie. Merci à toute ma famille, Julie et Raphaëlle, mes cousins et cousines, tantes et oncles, grand-mère, à la petite Saskia qui grandit si vite, vous rendez la vie plus belle. Merci aussi à mon beau-père, tu m'as accompagnée dans des années importantes de ma vie, où il a fallu faire des choix difficiles et l'amour que tu me portes m'a aidée à trouver la confiance nécessaire pour faire ces choix et avancer. Merci pour tes conseils éclairés.

Un immense merci à Thomas, ta sincère curiosité pour ton objet de recherche et ta passion pour celui-ci sont si rares et tellement précieuses, d'autant plus qu'elles ne vont pas seules mais que ta gentillesse, ton écoute, et ton humanité les accompagnent. J'ai hâte de tous les moments heureux que nous avons encore à vivre.

Contents

List of Figures

List of Tables

Chapter 1

General introduction

1.1 Context

Surgery has undeniable benefits for society contributing to both the saving of lives and to the improvement of its longevity and quality [33]. Yet, when looking closer at the numbers, estimates are that major morbidity complicates between 3-16% of all inpatient surgical procedures in developed countries, with permanent disability or death rates of about 0·4–0·8% [51; 76]. The estimated number of surgery in 2004 was between 187.2 million and 281.2 million cases per year [171]. Almost 7 million patients undergoing surgery have major complications, including 1 million that die during or immediately after surgery every year. Nearly half of the adverse events are identified as preventable. Possible prevention includes: organizational structure with strategic control of healthcare delivery, teamwork and leadership, evidence-based practice, training and education, availability of health information technology, proficiency, and well-embedded incident reporting and disclosure systems [29]. In the United States, public-health interventions and educational projects have significantly improved maternal and neonatal survival [137], so might analogous efforts in surgical safety and quality of care. In this thesis, the focus is on the improvement of training and education. To achieve improvement in this domain, two major challenges must be overcome.

The first being that surgery is complex, unstandardized, and requires long and diversified experience to be mastered correctly [68]. Learning to operate is a laborious process that requires to acquire a large number of diverse skills, some rather traditional, and other technology-oriented, sometimes coming into conflict. These diverse skills include: technical skills such as dexterity and knowledge of instruments, risks, procedures and anatomy, and non-technical skills such as formulation of the intervention plan, ability to make decisions, to lead, to work in team, situation awareness: gathering information and anticipating future (cf. fig 1.1). Thus, in this thesis, we address this challenge by considering the widest possible range of knowledge and skills required to master surgery. Although, the lack of time resources in particular did not permit to include non-technical skills in our experiments.

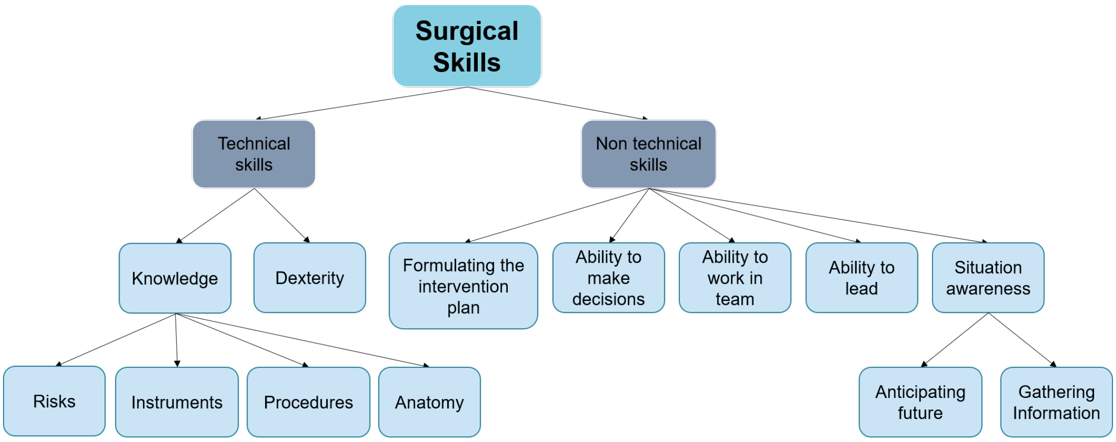


FIGURE 1.1: Surgical Skills

Surgical training traditionally takes place in the Operating Room (OR), but the growing number of students in residency from all specialities limits the number of opportunities to observe and thus learn to operate [118; 151]. As a result, medical students encounter difficulties when trying to compensate for the insufficient training inside the OR, which increases the number of possible mistakes when operating, decreases the opportunity to improve, and frequently results in them abandoning their specialization [18]. Technology such as videos (*e.g.* Augmented Reality (AR), Virtual Reality (VR), simulation) and physical simulators is an efficient mean to transfer outside of the OR part of the knowledge acquired inside of the OR, and thus to alleviate this issue. Still, often surgical trainers and technology developers put technology at the center of concerns and consider it as an end in itself, putting aside the pedagogical and learning aspects [132]. While many studies focus on the impact of different existing technologies on surgical training, few investigate the impact of learning theories and models implemented in these systems. This is partly due to the complex nature of surgical learning and to the fact that there are only few studies on surgical learning from a pedagogical or didactic perspective. This is the second challenge: the application of pedagogy and didactics to surgery and its implementation into technology. To explain the origins of the two main challenges cited, we are describing traditional surgical learning as well as new technologies for surgical learning, and both their limitations.

1.1.1 Traditional surgical learning

Surgery is traditionally taught through the apprenticeship model and its famous Halstedian "See one, Do one, Teach one" [82]. In this model, the student directly observes and then imitates the actions of a skilled mentor, both in the operating theater and in the clinical examination setting [40]. This model became the education standard when surgery evolved from a trade into a profession. The introduction of the apprenticeship model greatly improved surgical education, as now an experienced mentor instructs the trainee, shares collective knowledge, and teaches surgical techniques by demonstration and repetition. This change induced that surgical knowledge and techniques, though not scientifically studied to determine their benefit (or harm) to the patient or their success, were at least learned by instruction and example rather than trial and error [48].

Today, although the repertoire of tools available to the surgeon has increased, the attainment of safe and efficient surgical technique still depends on the same comprehensive knowledge of basic surgical skills. These include technical -proficiency in knot tying, instrument handling, suturing, haemostasis and tissue dissection [116]- and non-technical -the cognitive and interpersonal skills that complement practical and technical competences, such as decision making, leadership and team working- skills. In surgical specialties, these behavioural or non-technical aspects of performance (e.g. communication failures) are often the underlying causes of adverse events, rather than a lack of technical expertise. Traditionally, these aspects of performances have been largely developed informally rather than explicitly addressed in training [72]. They are the following: (a) Situation Awarness, (b) Decision Making, (c) Communication and (d) Teamwork, Leadership. (a) : Gathering Information, Understanding Information, Projecting and Anticipating future state. (b) : Considering Options, Selecting and communicating option, Implementing and reviewing decisions. (c) : Exchanging information, Establishing a shared understanding, Co-ordinating team activities. (d) : Setting and maintaining standards, Supporting others, Coping with pressure. However, both the traditional Halstedian model and the basic skills it aims to teach, are evolving. On the one hand, the Halstedian model is challenged, among other things, by the introduction of new technologies for surgical education. On the other hand, on top of the basic skills, new skills have to be mastered by attending surgeons with the arrival of new technologies for expert performance support.

New technologies induce major changes both in surgical education and surgical practice. Technologic advancements have at the same time improved learning by providing new resources for anatomy learning [25], real-time telementoring [144], clinical examination [28], problem-based learning [27] and procedural skills [24], and forced students to acquire new, technology-oriented skills. In this section, we start by briefly describing how the new technology resources are improving surgical training, and end by mentioning those which oblige students to develop new skills, having made a major entrance in ORs in the last decades to assist the expert surgeons: robots.

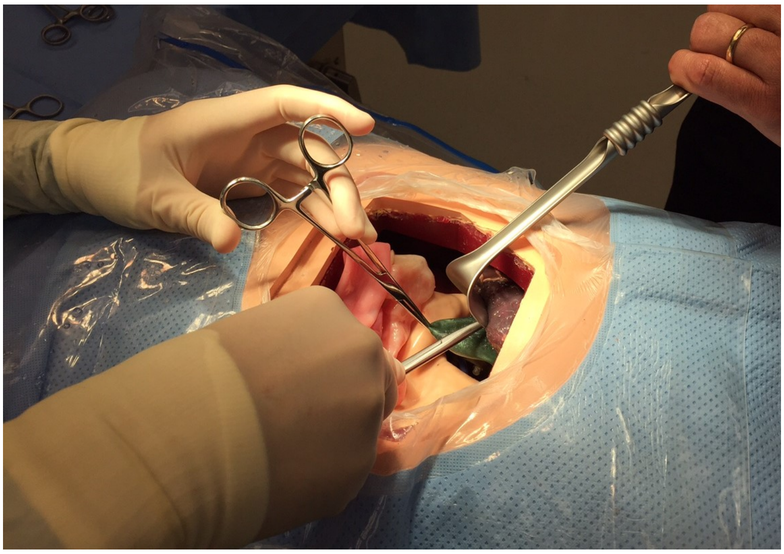


FIGURE 1.2: A physical simulator for surgical education by Vivonics Inc.

1.1.2 Existing technologies

In this section, the existing technologies for surgical training are detailed as exhaustively as possible. They are divided into the following categories: Video-based training, physical simulation and robotic-systems for learning. Each of these categories is not focused on training a particular skill and the boundaries between these different types of new technologies for surgical learning is thin, but typically video-based training are related with rather visual interactions than procedural training, physical simulators are rather related with procedural training.

1.1.2.1 Physical Simulators

Manikins A manikin refers to the concept of a full body patient simulator that safely allows for the training of clinical skills, cognitive thinking and behavioral communication in a professional healthcare setting (cf. figure 1.3). Other terms for manikin include human patient simulator, pediatric simulator, or surgery simulator. A manikin can range in its level of realism from a low-fidelity manikin to high-fidelity manikin. A low-fidelity manikin is a segmented clinical task trainer capable of a small number of specific tasks or procedures. A mid-fidelity manikin is usually a full-body simulated patient but with minimal computer components. A high-fidelity manikin incorporates the latest in computer hardware technology, is commonly wireless and can be programmed to provide for a very realistic full-body patient presentation. A high-fidelity manikin can be used a variety of high-stakes learning scenarios. Manikins help learners engage in patient assessment by providing cues as to the patient's state through the demonstration of vital signs such as pupil dilation, rate of pulse, rate of breath through chest rise and fall, or circulation through cyanotic discoloration. Manikins are used in many specialties.

FIGURE 1.3: A manikin for surgical training

Yet, evidence lacks on their impact on medical residents skills and knowledge. In a study by Nackman et al. from 2003, authors proved that training with them resulted in increased clinical knowledge and ability to manage complex critically ill patients [111]. Further research is needed to affirm with certainty their value in surgical education.

Robotic assistance With regards to robotics, a distinction must be made between assistance of learning and assistance of performance [67]. Several robotic assistance have made their entrance in the OR in the past thirty years, but not as assistance of learning. The great majority of them were designed to assist the expert's performance and later integrated simulations and VR training destined to develop skills on each specific robot and not to enhance traditional skills or alleviate traditional training -which must still be learned by medical residents and mastered in case technology would fail to work. The reason being that robotic assistance can easily improve performance when being used, but at opposite it is complicated to ensure that after the robot is turned off, surgeon who was using it for example, continues to perform as well as if s/he had never used it. A risk exists that the use of robotic assistance becomes "normal" and motor learning highly dependent on the robot specific dynamic environment.

With regards to learning assistance through robots, the majority of existing studies focus on describing one particular surgical robot and very few on surgical robotic features. In other domains, robotic assistance has proven helpful in improving motor skills for tasks of, for example, cursive writing [17], golf swinging [83], tennis stroke [100], pinball-like [104]. One study was found to examine the effect of haptic feedback on the learning curve of a complex laparoscopic suturing and knot-tying task [178]. The results are nuanced: learning with haptic feedback was significantly better than learning without it for a laparoscopic suturing and knot-tying task, but only during the first 5 h of training. The authors stress that the benefits of a shorter time to the first performance plateau and more consistent initial performance should be balanced with the cost of implementing haptic feedback in surgical simulators. Another study was conducted which integrated two robotics arms to a learning environment in the context of percutaneous procedures in orthopedics [94]. It is described more precisely later on in the thesis.

Different mechanisms qualify motor learning: reward-based learning, error based learning, observational learning and use-dependant learning [154]. These mechanisms result from neural changes in the brain. Assistive forces, or haptic guidance help observational learning and use-dependant learning whereas resistive forces, or error-amplifying modes help error-based learning. The risk with assistive forces is to encourage motor learning in a passive role. Conversely, error amplification requires adaptation to participants' level. It is known as the challenge point [58]: learning is optimal when a certain level of experienced error, and thus a certain level of experienced difficulty is attained. Also, modifying the task dynamics increases motor learning by improving the rate of adaptation to new task dynamics [136; 42].

Thus, it is important to encourage motor control by remaining active when performing the gesture. However, most of today's robotic assistance systems to surgery (e.g. the da Vinci [37], the PRECEYES Surgical System [103], the Mako Rio [54] etc.) are designed to ease or lower the active role of human motor control and learning. By changing the surgical gesture -to greatly facilitate it- they require students and education programs to adapt to a completely different set-up, and to develop new psychomotor skills together with technical knowledge on the system. We address this problem in our first experiment presented in chapter 2.

1.1.2.2 Video-based training

Video-based training in surgery includes the majority of existing training for surgery: immersive and non-immersive Virtual Reality (VR) simulation and Augmented Reality (AR) simulation, animated interactive videos, multimedia training, etc.

Virtual Reality simulators VR simulators can either be non-immersive or immersive. The difference in impact on training for each of these technologies still remains to be demonstrated.

Non-immersive virtual and augmented reality AR and VR is now a mature enough technology to be used for surgical training [132]. Some studies present results that show an absence of negative impact of non-immersive VR on the acquisition of skills in surgery compared with traditional training, including the technical competence to handle instruments and tissue deftly, knowledge of the flow of each surgical procedure and the surgical anatomy required to support this, and judgement about when to employ specific operative approaches and deal with complicated pathology [124]. A literature review on non-immersive AR and VR

FIGURE 1.4: A non-immersive virtual reality trainer by CAE Healthcare

and surgical education concludes that the evidence on their benefits is limited but suggests that these technologies may have a positive impact on the improvement of the speed acquisition of surgical skills, the ability to multitask, to perform a procedure accurately, hand-eye coordination and bimanualoperation [143]. Further research still needs to be conducted, with larger sample sizes, robust outcome measures and longer follow-up periods.

Immersive virtual and augmented reality Immersive videos are commonly known as video recordings where a view in every direction is recorded at the same time, shot using an omnidirectional camera or a collection of cameras. During playback on normal flat display the viewer has control of the viewing direction like a panorama. In this case videos used are 360° videos. An immersive video can also be a 180-degree video, monoscopic or stereoscopic video which captures only a 180-degree field of view, and allows more depth to be maintained by not subjecting the video to equirectangular projection: a stereoscopic 360-degree or 180-degree video which also captures depth and allows for six degrees of freedom in navigation within the captured environment. It can be played on a display or projectors arranged in a sphere or some part of a sphere.

We conducted a literature review on immersive VR and AR and its impact of surgical training and planing. Our work shows that VR seems to be particularly

FIGURE 1.5: An immersive virtual reality trainer for knee surgery by FundamentalVR

suited for surgical training, which is in line with previous works on immersive VR in education [132]. Our review reinforces the notion that immersive VR is relevant for surgical training in terms of self-confidence [130], performance [92; 91; 176; 90], and feeling of immersion [71; 70]. Regarding immersive AR, our study shows that there is very limited evidence on its interest both for training and planning. Both for immersive AR and VR, stronger evidence is needed and there are many directions for future research that can establish immersive AR and VR as crucial for training. These directions should include standardized protocols, the consideration of technological costs, the consideration for pedagogical aspects and the way they integrate in technological ones, the consideration for the inclusion of multiple perceptual senses, the measurement of clinical outcomes and of the evolution of non-technical skills. Indeed, regarding the multiple perceptual senses, further research should be conducted as immersive AR and RV augmented with robotic devices can allow to simulate surgical instruments such as in figure 1.5, an opportunity which is not systematically offered in the OR due to the risks to the patients. Finally, very few studies compare immersive vs. non-immersive VR, and thus we have limited insights on the trade-offs of each approach regarding its use as immersive or not.

Animated Interactive Videos: An interactive video gives the viewer the ability to interact with the video content itself through a variety of tools. Users can click, drag, scroll, hover, gesture and complete other digital actions to interact with the video's content, similar to the way they'd interact with web content. While animated videos are videos created with original designs, drawings, illustrations or computer-generated effects that have been made to move in an eye-catching way using any number of artistic styles.

Animated interactive videos are promising ways to improve surgical learning as, when interacting with dynamic displays, viewers are much more active in the learning process and the instruction can be tailored by the learner to his or her needs [63]. A meta-analysis by Augestad et al. from 2020 [11] shows that video-based coaching increases technical performance of medical students and surgical residents. Yet, the authors point out that there exists significant study and intervention heterogeneity that show the need to structure and standardize video-based coaching tools. In other domains, such as nautical not tying, interactive videos proved efficient in increasing the performance [141] but that is only if the videos interface is intuitive and allows to understand the essential features. This condition is frequently emphasized as animated videos are rarely developed in collaboration with Human-Computer Interfaces (HCI) experts. An interface to a dynamic visualization can be a source of extraneous cognitive load [153] that can take the viewer's attention away from the task of understanding and learning from the dynamic visualization.

Multimedia Training (Videos and Sound) Multimedia is media that combines different content forms, and can be defined as the integration of text, audio, images, animation, video, and interactivity content forms [74]. In a systematic review by Shariff et al. from 2016, [142], it is explained that multimedia is more suited for training of cognitive skills using procedural platforms (used to teach and assess surgical operations or procedures related to aspects of surgery). This may be, as the authors propose, because in addition to learning operation steps through text and images, multimedia can provide interactive, engaging visual information whilst simultaneously facilitating spatial orientation. Multimedia can provide engaging interactive visual information while facilitating spatial orientation. It can be of great use such as shown in one study were 360° videos significantly increased participants medical knowledge and self-reported confidence [49], or another where, compared with a non-video training group, video-training group was associated with improved resident knowledge, improved operative performance, and greater participant satisfaction [56]. Video-based training has potential for use in surgical education as it appears as an efficient way of overcoming the difficulties and barriers of the traditional apprenticeship model cited earlier, and according to a systematic review on video-based education in surgery by Ahmet et al. from 2018, this method is effictive and should be used in addition to standard techniques in the surgical education [5].

1.2 Problematic

1.2.1 The limitations of traditional surgical learning

While the apprenticeship model still remains the golden standard in surgical training, the changing practice environment due to resident work-hour restrictions (resulting in less opportunities to observe surgical practice) [30], the changes in the realities and legalities of the business of medicine (changes in reimbursement and other insurance and medico-legal issues) [16] and the shift in practice pattern [39] has induced the development of competing models [129]. Trainees today may have limited exposure to certain procedures, anatomical variations, or management of intraoperative and postoperative complications. Thus, there is a need for complementary strategies that expose trainees to a greater breadth and depth of surgery [8]. Additionally, the introduction of new technologies, rapidly evolving and ever more numerous, force surgical students to keep adapting and continuously acquire more technology oriented skills on top of traditional skills.

1.2.2 The limitations of new technologies for surgical learning

Indeed, while new technologies for surgical education offer many opportunities for the improvement of training, inside and outside the OR, they also show numerous and hard to overcome limitations. One of the greatest limitations is their important cost, which results in their scarcity and makes them hard to access. Furthermore, there is a serious lack of evidence on the transferability of skills and knowledge acquired using new technologies, to the OR. This is in part due to the unpredictable nature of the events occurring in the OR making evaluation hard to standardize, and to the lack of time for evaluation in the OR. Still, this information is essential in the assessment of their value. To better define the limitations of existing new technologies for surgical training and the consequences of these limitations, in this thesis, a study is conducted which aims at interrogating 1st year medical residents (presented in Chapter 3) and an other study is conducted which evaluates the impact of a techno-pedagogical surgical training on knowledge and skills of 1st year medical residents under real-life conditions (presented in Chapter 4). In addition to these limitations, transversal to all new technologies for surgical education, other emerge which are specific to surgical robotic systems and which are specifically addressed in Chapter 2.

Robotic systems, which were initially introduced in ORs as an assistance to the expert surgeons, now have become omniscient. They thus require the surgical student to train on them. As these systems greatly alleviate surgery arduousness, in particular laparoscopic (a type of surgical procedure that allows a surgeon to access the inside of the abdomen and pelvis without having to make large incisions in the skin) [4] and sometimes improve surgical outcomes, they require surgeons and future surgeons to spend time learning dexterity skills only applicable to one robot. It is time where, at least for surgical students, they are not learning the essential procedural knowledge or the non-technical skills related to surgery.

These robot-related dexterity skills sometimes even negatively impact the traditional skills that surgeons and future surgeons are required to master throughout their whole career [19; 20], in case technology failed to work, or in the case of any other adverse event. Most of the robotic assistance to surgery did not incorporate in their design the continuity of dexterity skills already mastered or in the process of being mastered by the students. New technologies for surgical training are great tools and a very adapted solutions to today's constraints in surgery, but they design requires to be reflected with regards to medical residents and expert already mastered skills and tight agenda.

Generally speaking, although being very interesting tools to alleviate the difficulty of the surgical practice (in terms of fatigue, the need for precision and accuracy, difficulty in accessing narrow areas of the human body), new technologies for surgical learning have limitations as they are either focused on dexterity or knowledge but rarely both, too technology-centered rather than human centered, and sometimes in conflict with traditional surgical skills. They lack consideration for the learner: his/her needs, previous knowledge, constraints, learning methods, motivation etc. Thus, the goal for surgical educators in to capitalize on the various existing technologies and to adapt to the learner, without lacking consideration for his/her core experiences and skills.

1.3 Contributions

This thesis aims at proposing ways to address the difficulties encountered by surgical students by covering as many surgery-related skills as possible, and by focusing on the pedagogical aspects rather than the technological, only used as a mean to convey surgical training.

Chapter 1 presents traditional surgical learning as well as new ways to learn surgery induced by technologies, both their limitations and our contributions to address these limitations.

Chapter 2 presents existing interaction designs for robotic-assisted surgery and more specifically comanipulated robot-assisted surgery, the skills they train and the quantitative methods to measure these skills acquisitions. This chapter then introduces an experimental protocol focused on dexterity, aiming at exploring ways of reducing existing discrepancies between the learning of traditional dexterity and of technology-oriented dexterity in surgery.

In chapter 3, the existing application of pedagogy and learning theories to surgery and the qualitative methods to measure surgical learning are presented. We also describe an exploratory study that aims at measuring the impact of learning and pedagogy theories in the design and production of a surgical training, putting aside the technological considerations.

In chapter 4 the concept of techno-pedagogy is explained, whose purpose is to reconcile pedagogical and didactical considerations with technological ones. An experimental protocol is detailed, that aims at presenting a possible techno-pedagogical surgical training.

The goal of the thesis is to present guidelines in the development of learning modules in surgery that integrate a pedagogical guidance: regarding systems that aim at developing dexterity, the absence of negative impact on the skills previously mastered; in the case of systems that aim at developing the knowledge on the surgical intervention, the development of knowledge that is more structured, portable, and meaningful. Finally, by proposing ways to link these technological -and rather focused on technical skills- and pedagogical -and rather focused on knowledge and non-technical skills- devices, this thesis aims at showing the possibility of a continuum between these different material for surgical education which each cover different skills needed to perform surgery, presented in figure 1.1.

1.4 Publications

During this thesis, several answers to problems concerning surgical education were proposed which lead to one article publication and two articles submission (ongoing)

- Eléonore Ferrier-Barbut, Philippe Gauthier, Vanda Luengo, Geoffroy Canlorbe, Marie-Aude Vitrani. Measuring the quality of learning in a human-robot collaboration: a study of laparoscopic surgery. ACM Transactions on Human-Robot Interaction, ACM, In press. ⟨hal-03355055⟩
- Eléonore Ferrier-Barbut, Philippe Gauthier, Geoffroy Canlorbe, Marie-Aude Vitrani, Thomas Dabreteau, Vanda Luengo. Knowledge-based surgical training: impact on knowledge, skills and experience. Manuscript submitted for publication.
- Eléonore Ferrier-Barbut, Ignacio Avellino, Philippe Gauthier, Geoffroy Canlorbe, Marie-Aude Vitrani, Thomas Dabreteau, Vanda Luengo. Head Mounted Displays in Surgical Training and Planning: A Literature Review. Manuscript submitted for publication.

This thesis also led to the deposit of a Soleau envelope on the shooting of videos in the operating room to create video-based learning scenarios.

Finally, during this thesis, the work were presented during different seminars: ISIR PhD day 2018/2019/2020, a workshop on surgical robotics held by the University of Lorraine 2018, the Surgical Robot Challenge held during the Hamlyn Symposium 2019, Surgetica 2019, Doctoral School SMAER PhD day 2019, video session at CAMI Days 2020, the Fall of Science 2021 programs held by the city of Paris.

Chapter 2

Robotic assistance and surgical learning

This chapter describes the state of the art in terms of technology and surgical learning, enabling to discuss the existing limitations. A first study is presented, on the impact of learning robot-assisted surgery on previous skills in classic surgery.

2.1 State of the art

2.1.1 Interaction Designs Surgical robotics

Robotic surgery is increasingly used in Operating Rooms (ORs), for a number of surgeries, including prostatectomies, cardiac valve repair, and gynecologic surgical

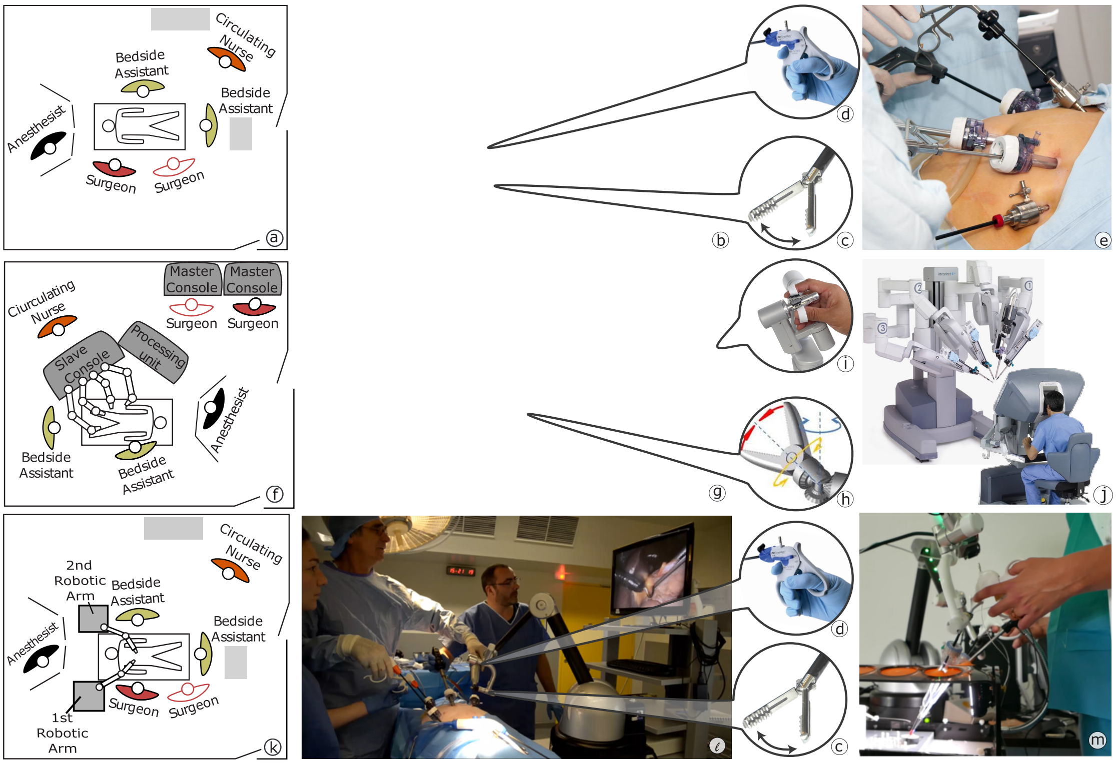


FIGURE 2.1: CLS (Top); Tele-RALS (Middle); Co-RALS (Bottom). A CLS OR diagram **(a)** and an image of an OR in CLS **(b)**. Mechanical tools **(c)**, activated by pulling a trigger and a rotation knob **(d)**. Surgeons insert instrument through small holes **(e)**. Tele-RALS OR diagram **(f)** and and image of an OR in Tele-RALS **(g)** where a surgeon works at the master console and two assistants at the bed side. Moving joysticks **(i)** control tools **(h)** on the robotic arms at the slave console **(j)**. Co-RALS OR diagram **(k)** and image of an OR in Co-RALS **(l)**. Same tools as in CLS are used **(c)** manipulated the same way **(d)**, while gestures are secured and improved by the robotic arms **(m)**. *Extended from "Impacts of Telemanipulation in Robotic Assisted Surgery." by Avellino, I., et al. [12]. Extended with permission.*

procedures. The *Da Vinci* **(cf. figure 2.1-j)** is by far the most widely used one with over 1 million procedures performed in 2018 [152]. This robot aims, along with many other to make laparoscopic surgery less arduous. It accelerates the learning curve [4] and improves dexterity compared with classic laparoscopic surgery [108] but its clinical advantages have yet to be proven [4]. Without robot, *e.g.* Classic Laparoscopic Surgery (CLS) **(cf. figure 2.1-e)** is surgery done through small holes in the patient's belly, in which are inserted long instruments and a camera *i.e.* endoscope. The image of the endoscope is displayed on a 2D screen, showing the inside of the patient's body. CLS is advantageous for patients (less pain, shorter recovery, aesthetic benefits) but disadvantageous for surgeons who then have more visual as well as physical difficulties to deal with than in open surgery. Visual difficulties are partly generated by the absence of direct vision. The working space is visualized on a 2-dimensional screen while gestures are performed in a 3-dimensional space, making hand-eye coordination and depth perception complicated [36]. Physical difficulties are due to the length of the instruments and to the fact that their insertion point (the small incisions in the patient body) induces kinematic restrictions and the appearance of the fulcrum or lever arm effect [114]. Robot-Assisted Laparoscopic Surgery (RALS) aims to alleviate varying difficulties depending on the robot's interface and features.

There are two interaction designs for Robot Assisted Laparoscopic Surgery (RALS): telemanipulated (Tele-RALS) **(cf. figure 2.1-f)** such as with the *Da Vinci* and comanipulated (Co-RALS) **(cf. figure 2.1-k)**. In Tele-RALS, as indicated by the semantics, a distance exists between the surgeon (who sits at the master console) and the patient (above who stand the robotic arms holding the instruments, the slave console). This distance removes the hand-eye coordination and the physical difficulties as instruments situated at the slave console are controlled with joysticks situated at the master's console thanks to a communication channel between the two. However, it introduces new difficulties. To use the robot surgeons and future surgeons have to learn, on top of traditional skills linked with Classic Laparoscopic Surgery (CLS) more technology-oriented skills. Comanipulation, contrarily to the other design for surgical robot, telemanipulation, is a robotic assistance that allows for skill transfer to occur from robot-assisted mode to without robot mode by maintaining a role of motor and learning. In our first experiment, we focus on comanipulated robotics, a design which precisely aims at maintaining motor control active role and from which we have developed an experimental protocol.

2.1.2 Comanipulated Interfaces in Robotics

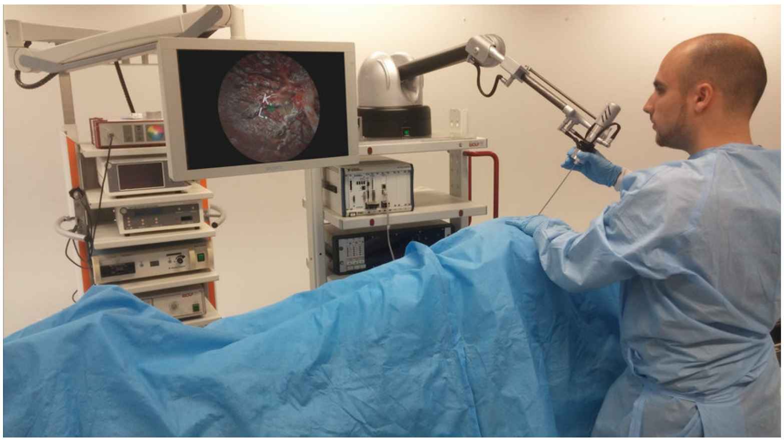


FIGURE 2.2: A comanipulated set-up for foetus surgery [57]

The definition of comanipulation can be found in Morel et al.'s article from 2013: *A comanipulator is thus any robotic system performing a task, most often in contact with the environment, that can be controlled through direct contact by an operator. It aims to increase the manipulation performance of the operator* [109].

The interaction design of comanipulation in robotics is derived from the concept of cobotic, a term invented by J. Edward Colgate and Michael Peshkin in 1996 [123]. A cobot, or collaborative robot, is a robot intended for direct human robot interaction within a shared space, where humans and robots are in close proximity. Cobot applications are in contrast with industrial robot applications, which imply that robots are isolated from human contact. Comanipulation is an interaction paradigm involving a robot and a user simulta-neously manipulating a load or a tool. The robot is employed as a comanipulated device, in the sense that the gesture control of the instrument is shared by the robot and the surgeon. Of the difficulties of CLS mentioned earlier, comanipulation aims to facilitate the physical ones in particular. The currently existing commercialized comanipulated robotic systems are basically designed for specific types of surgical tasks in knee replacement surgery [75], knee arthroplasty [121], placement of intracranial depth electrodes [73], [45]. Research institutes have also exploited the idea for precise surgical tasks such as the positioning the tip of an instrument inserted through an orifice [22]. Comanipulation can be applied to tasks that require both precise manipulation and human judgment so as to enhance gesture quality [155]. This interaction design for robotics has the ability to at least compensate for gravity and filter tremors [126] while performing the surgical gesture. Some other physical difficulties can also be dealt with including the reduction of the fulcrum effect for example with the help of an an active force feedback [140].

A comanipulated robotic assistance, such as the Acrobot [75], aims to improve security and dexterity when performing the surgical gesture while keeping the surgeon close to her/his patient. Comanipulation means the shared control of the instruments by the robotic assistance and the surgeon [109]: both the robotic arms and the user hold the instruments needed to perform the surgery. Same as for laparoscopic surgery, while technically possible to perform viewing the image of the endoscope in 3D, Co-RALS is most frequently performed viewing the image of the endoscope on a 2D screen. This design is at the fourth degree of human-robot collaboration scale [64]: Supportive. At this level, the human and the robot work together at the same time and with the same workpiece to complete a common task. Arguably, a successful *Supportive* human-robot collaboration is defined by its ability to augment performance compared to the same task performed without a robot, but also to confer to the human a cognitive and physical load that is neither too important nor too little, to diminish the difficulty of the task while keeping the human involved and active [117].

For a task as complex as surgery simultaneously performed by a human operator and a robot, where robots are far from being able to replace the human operators, it can be suggested that keeping the human involved and active is mandatory, for him/her to maintain his/her acquired skills level. Indeed, in surgery, the robot assists the human in a task s/he already masters. Comanipulated robots for surgery are destined to work very closely with surgeons and future surgeons without disturbing their dexterity skills and while increasing their performance. The robot only augments already existing technical skills.

Still, learning with a telemanipulated robot was shown to negatively impact the traditional skills that surgeons and future surgeons are required to master throughout their whole career [19; 20], in case technology failed to work, or in the case of any other adverse event. This negative impact on the learning process was not considered by designers. A change in this direction is strongly recommended, through the conduct of experimental protocols on surgical learning and robot assistance. It starts with a thoughtful and well-considered choice of the measuring tools for surgical learning. They are a major component of this reflection, to the extent that measurement method also defines what is qualitative learning and how to improve it.

2.2 Quantitative measurement of learning

2.2.1 Gesture tracking

A very frequently used method for measuring surgical learning is motion tracking of the surgical instruments. The gesture is analyzed through the tracking of the instrument motion, either at its tip, or at its handle. Measures such as economy of movement have been shown to significantly differentiate a novice and an expert [50], and to be correlated with the FLS standard scoring and motion efficiency metrics [175]. Other metrics such as movement smoothness, path length, mean velocity, bimanual dexterity, working volume have also been used to differentiate between novice and expert level in laparoscopic surgery [35]. Motion tracking serves as a way to observe learning curves in the acquisition of the gesture, or rather, generally, learning curves showing the evolution of the proficiency in using a surgical tool. Oftentimes, a comparison is made between experts and novices when performing exercises of surgery such as in Herman et al.'s work from 2011 [65] in a more or less realistic context, *i.e.* integrating a varying number of elements needed to correctly perform the gesture in a realistic context.

Still, gesture tracking as a measuring tool and its associated metrics, while succeeding in showing movement efficiency, fail to show movement quality. Gesture tracking measures dexterity efficiency independently from any other measure of quality of the gesture which makes using this measuring tool highly questionable, and as Smith et al. mention in their article from 2002 “It is of no use to be smooth and efficient with one's movements, if a clip is then placed on the bile duct.” [148]. For this reason, other methods for learning measurement in surgery have emerged, such as eye and gaze-tracking.

2.2.2 Eye and gaze tracking

In other domains than surgery, such as motor control and aviation, gaze-tracking proved to be an efficient way of observing eye-hand coordination, anticipation, information gathering and planning [139; 138]. In surgery, especially laparoscopic, eye and gaze tracking also proved several times to be efficient in showing eye-hand coordination skills [87; 172; 174; 62; 66]. The process of eye tracking involves three main steps; to discover the presence of eyes, a precise interpretation of eye positions, and frame to frame tracking of detected eyes. The position of the eye is generally measured with the help of the pupil or iris center [6]. Gaze estimation is a process to estimate and track the 3D line of sight of a person, or simply, where a person is looking. Experts have a greater ability to anticipate their gestures with their gaze than novices. This results, in tasks of target reaching, in a greater ability to look at the aimed target rather than the instruments used to reach the target. In other words, experts anticipate their movement by taking their eyes off it and projecting them to its goal, while novices are focused on achieving the movement itself and keep their eyes on it. This translates into a struggle to detach their eyes off their hands or the instruments they hold to perform the movement and to project their gaze to its goal. It can be measured by the number of fixations (the maintenance of the gaze in a single location) on the aimed target before reaching it with the instruments, a greater number meaning a better ability to anticipate, and greater expertise [9]. Experts also tend to do less back and forth movements with the eyes -movements used by novices to make calculations of distances, lengths, velocities- and a smaller number of fixations. The duration of their fixations also tends to be larger than for novices.

We used gaze tracking as a measuring tool to study the transfer of skills between robot and classic laparoscopic surgery, an experiment that is described later on.

2.3 Transfer of skills between classic and robot-assisted surgery

In the case of laparoscopic surgery, the type of surgery that is majorly targeted by robotic assistance, mastering classic laparoscopic surgery appears as an advantage in the mastering of robot-assisted surgery. In a study by Angell et a. from 2013, the performance of a complex robotic task in laparoscopic surgery was improved by laparoscopic training [7]. The authors suggest than laparoscopic training improves the proficiency in operation of the robot. In an other study by Abaza et al. from 2009 [2], the authors suggest that there are many aspects of robotic surgery that benefit from laparoscopic skills such as access, placement of ports, addressing of adhesions or other anatomic variations, instrument handling in the often narrow and potentially disorienting laparoscopic space and strategies for adjusting to the environment that are not a part of traditional open surgical training. However, as we will see later, the reverse -the transfer of skills from RALS to classic- is not necessarily true.

2.3.1 Impact of robotic interfaces on non-technical skills

Numerous articles in the field of Human Computer Interfaces (HCI) have focused on the impact of interfaces for RALS on non-technical skills [177] related to laparoscopic surgery: workflow, communication, situation awareness, teamwork [12; 122; 23; 133; 134; 135]. These works are exclusively on Tele-RALS, and the metrics used are essentially subjective. These robotic systems enhance the surgeon's experience by making them more independent to perform surgery and increasing the number of instruments they can control. But the distance imposed with patients keeps them away from their team. This physical distance is compounded by visual, auditory and mental distances. It disrupts access to information, changes power distribution and decreases the surgeon's situation awareness. It also has consequences for students who then have fewer tasks, decisions and actions to make [169] than when the surgical intervention is performed without the robot. Their learning process is made more difficult: they can no longer learn by observing, hearing, and doing according to the well known wording *See one, do one, teach one* [125] as they are not standing next to the surgeon any more [107].

2.3.2 Impact of robotic interfaces on technical skills

Although less studied, the impact of interaction design for robotic assistance on technical skills [115] related to laparoscopic surgery is just as strong. The interaction design for robotic surgery defines the nature and the difficulty of motor skills either learned or mastered by the user, and how they transfer to without robotic assistance. Robotic assistance can easily improve performance when being used. However, as stressed in a review of literature on robotic assistance of motor learning by Heuer et. *al's* from 2015 from the field of neurosciences, it is complicated to ensure that after the robot is turned off, the user continues to perform as well as if s/he had never used it [67]. A risk exists that the use of robotic assistance becomes "normal" and the motor learning highly dependent on the robot specific dynamic environment.

This situation would lead to a negative impact of training with a robotic assistance on skills mastered in the classic technique, as it seems to be the case for Tele-RALS [19; 20]. Both these studies by Blavier et al. from 2007 were conducted with medical students without any prior surgical experience and results suggest that training in Tele-RALS has negative consequences on mastery of skills in CLS, compared with training in CLS alone. In the case of a conversion from Tele-RALS to CLS during a surgical intervention, a scenario that regularely happens for different reasons such as mentioned in Blavier's et al. article from 2007 [19], this negative impact can have major consequences. For this reason, we conducted an experimental protocol on the transfer of skills from Comanipulated Robot-Assisted Laparoscopic Surgery (Co-RALS) to Classic Laparoscopic Surgery (CLS), to explore the possibility of a robotic assistance that facilitates the surgical gesture without disrupting the learner's core dexterity skills and even hypothetically improving them.

2.4 Our Approach: from robot-assisted surgery to classic

In the first experimental protocol of this thesis, we study the transfer of skills from Co-RALS to CLS. We hypothesize that training in Co-RALS results in equivalent hand-eye coordination and time-wise abilities compared with training in CLS. Hence we take a different approach than previous work: with objective metrics, we seek to observe the quality of the human-robot interaction through the analysis of the skills developed by the human in conjunction with the performances achieved by the human-robot team.

(A) (B)

FIGURE 2.3: (a) CLS Set-Up (b) Co-RALS Set Up

Two comanipulated robotic arms are used **(cf. figure 2.3A)**. One for each instrument manipulated when performing exercises in laparoscopic surgery. Only the basic functions of the robots are studied. Gravity compensation for instruments is ensured, as well as tremor filtration. The algorithm used for tremor filtration is a viscous field, *i.e.* a damping algorithm proportional to the velocity of movement [38]. The robots exhibit high viscosity at low velocities and no viscosity at high velocities, at the instrument tip. It helps the surgeons during precise surgical tasks (performed at small speed), by filtering unintentional movements and augmenting precision of the gesture. This viscous field also increases the rate of adaptation of the user, forced to remain active when performing her/his task.

A similar algorithm, implemented in a comanipulated robotic assistance where the human controls the direction and the speed while the robot ensures the precision and smoothness of motions by suppressing sudden and abrupt gestures, has been shown to significantly improve performance for tasks of manual welding [43]. In an other research article [160], a human robot cooperative calligraphic task is performed, in which the human and the robot grasp a writing brush at the same time. The robot is controlled against the human force to prevent the vibration and to enhance the accuracy, and results show the advantage of the control method. The benefits of variable damping coefficient have been demonstrated. Thus, referring to the second question of research, it is hypothesized that in Co-RALS, the adaptive damping algorithm implemented enables better time-wise performance for exercises of laparoscopic surgery compared to the same exercises performed without the robotic assistance.

Here, we study the learning period when surgeons simultaneously learn to perform classic (without robot) and robot-assisted laparoscopic surgery. During this period, the discrepancy between psycho-motor skills required to perform the two techniques is problematic. Most importantly since learning laparoscopic surgery with a telemanipulated assistance does not result in a transfer of skills to the classic technique [20], a situation that requires re-learning for each switch between techniques.

We propose a method to measure with quantitative metrics, how a collaborative robotic assistance not only can help to increase performance and learning in very complex tasks but also the impact it has on the technical skills mastered by the human. We study it through two research questions, situated in the specific context of learning when the acquisition of skills is of crucial importance.

The **main research question** is the following: does training with a co-manipulated robot in what we call a *target task*, in our case exercises of laparoscopic surgery, develop hand-eye coordination and time-wise skills in this target -and simultaneously learned in a surgical curriculum- task? We focus on the hand-eye coordination skills as these are especially complex to learn and perform in laparoscopic surgery. Indeed, laparoscopic surgery may require specific mental abilities, such as spatial orientation and mental representation [32; 3; 96]. To measure the hand-eye coordination skills, we use a tool that to our knowledge has rarely been used in Human-Robot Interaction: gaze tracking. The number of fixations (the event when the gaze remains on a point for 50 to 600 ms [86]) on the aimed target, the fixation rate per second and the duration of fixations, when performing in CLS are measured either after training in Co-RALS or in CLS. Previous works have shown that these metrics enable to measure hand-eye coordination skills developed when training [62], in laparoscopic surgery especially [172; 173; 87]. To measure time-wise skills, time elapsed is recorded when performing exercises in CLS, either after training in Co-RALS or in CLS. This shows the operator's performance efficiency [101] in the *target task* after training in Co-RALS.

The **secondary research question** is the following: does using Co-RALS improve time-wise performance on exercises of laparoscopic surgery compared with the same exercises performed in CLS? Time elapsed is also recorded when performing repeated exercises with each technique. The repetition of the exercises highlights the shapes of the learning curves. Other metrics are used as exploratory measures: the NASA TLX [61] that serves to compare the workload between the robot-assisted technique and the classic technique, and a performance score given for the exercise performed in the classic technique either after training with the robotic-assistance or without.

2.4.1 Methods and Material

TABLE 2.1: Experimental Protocol: exercises in bold are those during which data is recorded. The others are familiarization exercises. The order of exercises performed during the Learning Step is randomized.

Group	Pre-Learning Step	Learning Step	Post-Learning Step
Classic	Task CLS Peg Tran. Dom. (4') **Peg Tran. Non Dom. (4')**	Task CLS **Pea on a Peg (30')** **Loops and Wire (15')**	Task CLS Peg Tran. Dom. (4') **Peg Tran. Non Dom. (4')**
Robot	Task CLS Peg Tran. Dom. (4') **Peg Tran. Non Dom. (4')**	Task Co-RALS **Pea on a Peg (30')** **Loops and Wire (15')**	Task CLS Peg Tran. Dom. (4') **Peg Tran. Non Dom. (4')**

To investigate 1. whether training with a comanipulated device in laparoscopic surgery results in an equivalent development of skills in this *target task*, exercises of laparoscopic surgery, compared with training in the *target task* and 2. the comparison of the learning curve between the robot-assisted task and the classic task, we present an experimental protocol involving two conditions. The participants in *Classic* condition are pre-tested in CLS during the *Pre-Learning Step*, then trained in CLS, and then post-tested during the *Post-Learning Step* in CLS. The participants in *Robot* condition are also pre-tested in CLS, then trained in RALS, then post-tested in CLS (**cf. table 2.1**). Both groups are Pre-trained and Post-trained in the same task, CLS, to compare the differences in the process of learning for each group, *Classic* and *Robot*, in CLS. The main research question is studied by comparing the skills in CLS of the two groups, *Classic* and *Robot* with gaze-tracking and time recording, and the secondary research question by comparing the learning curves of the two groups *Classic* and *Robot* during their learning session with time recording. The exercises of laparoscopic surgery performed at each step were chosen among basic training exercises for this discipline, depending on the skills they enable to train and measure.

During the Pre and Post-Learning steps, the exercise chosen was the Peg Transfer as it enables to observe a large panel of participant's skills in laparoscopic surgery: bimanual coordination, precision, and depth perception. It requires the participant to lift six objects place on the left side of a board with a grasper first using non-dominant (in this case, left) hand and transfer the object midair to the dominant hand. Then, the participant has to place each object on a peg on the right side of the board. It is also performed from dominant to non-dominant hand. This exercise is further described later on. Pea on a Peg and Loops and Wire were chosen because they trained precision and depth perception respectively. Exercise Pea on a Peg consists of placing 14 beads on pegs of different highs placed on a board, and exercise Loops and Wire consists of passing a wire through 4 different loops placed on a board. Both these exercises are also further described later on. The fact that each exercise trains different skills enables to better define the differences between CLS and Co-RALS in terms of learning.

This experimental protocol is tested both with Resident participants and, more numerous, Non-Resident participants. The similarity of the exercises in laparoscopic surgery performed by each group is controlled. Level equivalence between group Robot and Classic is statistically verified for Non-Resident participants during the *Pre-Learning Step*. There were not enough Resident participants involved in the protocol to perform this verification, hence the Resident participants' results are presented as indication of tendency and insights for future research rather than results that can be generalized. The experiment is thus divided into three steps: 1. A pre-learning step to control the participants' level, 2. A learning step to train the participants of each group respectively in each task and (CLS and Co-RALS) and compare their performance and 3. A post-learning step to compare the mean level of each group in the target activity, *i.e.* CLS.

2.4.1.1 Participants

Fourteen Non-Resident participants and six Residents in medicine are recruited. Among them, seven Non-Resident participants and three Resident participants (group Classic) performed their training session in in CLS (task CLS). Seven other Non-Resident participants and three other Resident participants (group Robot) performed their training session in RALS on a comanipulated robot (task Co-RALS). Resident participants have a small and contrasted experience in laparoscopic surgery (6 ± 4.5 hours of practice). The number of Resident participants involved in the study does not allow to perform statistics. Still, their results enable to verify whether the trend observed among novices may be applied to intermediate level users. Because of their tight agenda, Residents in medicine could only perform one exercise, *Pea on a Peg*, during the training session and, due to a lack of technical and time resources, no gaze data could be recorded during *Peg Transfer* exercise before and after the Learning session. Their results are presented separately. Five of them are first year residents and one is third year resident. Non-Resident participants all declared to be novices in laparoscopic surgery, and are all university students. All procedures are in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

2.4.1.2 Apparatus

Material includes two set-ups: one in CLS, and one in Co-RALS.

Task CLS. *The CLS set-up*: It includes two surgical graspers. Exercises are performed in a pelvi-trainer, above which is a 2D screen transcribing the 3D working space inside it **(cf. figure 2.3A)**. The endoscope does not move during the entire learning session.

Task Co-RALS. *The Co-RALS set-up*: It consists of two robotic arms, each holding the same two graspers as those used in the CLS set-up. **(cf. figure 2.3B)**. The two robotic arms are modified Haption Virtuose 3D robots, characterized by six rotational joints. The robots used are 3D robots as other degrees of freedom are constrained by the entree point in the patients' belly **(cf. figure 2.4)**. The first three joints are fully actuated and the other three form a free wrist that allows full motion across the surgical workspace [98]. Our research team designed the software implemented in these robotics arms: (i) tool weight compensation so that holding the tools is transparent to surgeons [156] and (ii) a damping algorithm proportional to the velocity of movement, experimentally tuned such as in [38; 89]. The same pelvi-trainer as for the CLS set-up is used **(cf. figure 2.3A)**. The endoscope is not moved during the entire learning session.

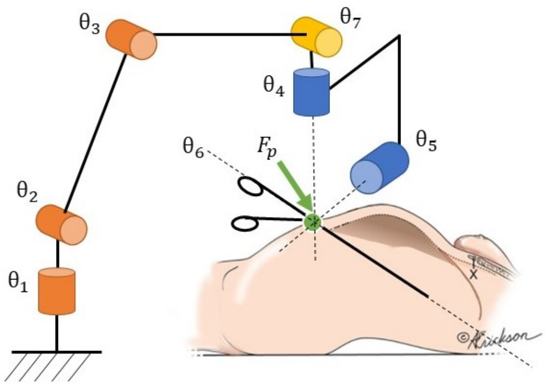


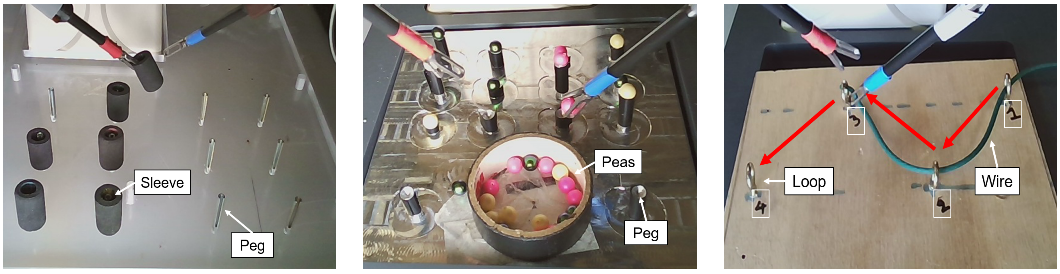
FIGURE 2.4: A scheme of the kinematic chain of the robot (from [46])

2.4.1.3 Measuring tools and metrics

Different measuring tools and metrics are used at each step of the experiment to assess hand-eye coordination abilities, time-wise performance and, workload and scores. They were chosen for their ability to show not only the observed performance at the end of a task but also the learning process itself. **Gaze-tracking** is used during the Pre-Learning Step to verify the absence of heterogeneity in average hand-eye coordination skills in laparoscopic surgery of groups Classic and Robot before the Learning session. It is also used during Post-Learning step to quantify for differences in the same skills between these groups after the Learning session. **Time** is recorded at each step of the experiment. Before and after the Learning session this metric enables to answer the first research question, together with gaze-tracking. During the learning session, Time recording serves to answer the secondary research question. The results obtained at the **NASA Task Load Index** during the learning session and the scores at the *Peg Transfer* exercise are explored, respectively as self-perceived feeling of comfort with the task and observed performance.

Pre-Learning Step

- Gaze-Tracking: Observing gaze pattern has been proven to be relevant in distinguishing novices from experts [172; 87; 174; 62]. Hence, **the number of fixations on the aimed target** before it has been reached with the instruments, **fixation rate per second** and **duration of fixations** are analyzed. A higher **number of fixations on the aimed target** at the specific moment of reaching for the target in the Peg Transfer means a greater level of comfort with the task. At the opposite, less **fixations per second** and greater **duration of fixations** while performing the entire exercise means better hand-eye coordination skills. Gaze data analysis is performed separately for each phase of the *Peg Transfer* exercise described later on in the article. It is cut into 3 phases: *Grab*, *Transfer* and *Drop*. *Grab* corresponds to the moment where participants grab the bead with their dominant hand, *Transfer* to the moment they pass it to their non-dominant hand and *Drop* to the moment they put it on the peg. The *Transfer* and *Drop* phases are the most interesting. They represent the moment where the participants are specifically doing a target reaching task. Recording gaze data enables observation of hand-eye coordination abilities. The Eye Tracker used to record gaze data is a Tobii X3-120 screen-based eye tracker with a sampling rate of 120Hz. It is mounted at the bottom of the screen at the eye level of participants. Data analysis is performed with Tobii Pro Lab and the filtering algorithm used is the IV-T Classifier. To identify **the number of fixations on the aimed target**, we manually defined, using Tobii Pro Lab, dynamic zones of interest. They were the zones, on the 2D screen, aimed by the participants when performing the *Peg Transfer* exercise described later on. Statistics of the number of fixations in these zones can then be extracted.
- Time: A timer is set during performance of exercises.
- Score: Videos of the camera used to perform the exercises is recorded to allow for scoring of the *Peg Transfer* exercise. 10 penalty points are counted per dropped sleeve. When a sleeve falls from the pegboard 20 penalty points



(A) (B) (C)

FIGURE 2.5: (a) Peg Transfer (b) Pea on a Peg (c) Loops and Wire

are counted. Total score is time in seconds + penalty points. This score shows temporal as well as qualitative performance.

Learning Step

- Time: A timer is set during each trial of the two exercises performed during the learning session, described latter on in the article.
- NASA Task Load Index (TLX): It is used as an exploratory measure of comfort level with the executed tasks during the learning session. This index is a subjective, multidimensional assessment tool that rates perceived workload in order to assess a task, system, or team's effectiveness or other aspects of performance. It was developed by the Human Performance Group at NASA's Arms Research Center. The higher the score is, the more important is the perceived workload. In this study, the score is NASA weighted. Participants were required to fill the NASA TLX after they had performed the learning session.

Procedures: Experiment is divided into three steps **(cf. table 2.1**):

Post-Learning Step The measuring tools and metrics are the same as during the *Pre-Learning Step.*

Pre-Learning Step This step consists in the measurement of participants' base level. The data recorded enables to ensure that the two groups of participants: Classic and Robot do not show, initially, significant differences in level in the target activity. Means of each group before the learning session are compared to check for statistical differences.
The exercises performed are the following:

- *Peg Transfer Non Dominant*: familiarization exercise, data is not recorded during this task because it is the familiarization task, during which participants discover instruments and set-up for four minutes. There are 6 sleeves and 12 pegs on the board. The 6 sleeves are positioned on 6 pegs, on one side of the board. Subjects have to transfer the sleeves from one side of the board to the other. To pick up a sleeve, they use the instrument held in the non dominant hand. Then they transfer the sleeve to the instrument held in the dominant hand. Maximum time is 4 minutes.

- *Peg Transfer Dominant*: recorded exercise. Subjects have to transfer sleeves resting on pegs on the other side of the board. They pick the sleeves up with the instrument held in the dominant hand, transfer them in the instrument held in the non dominant hand, drop them on the other side of the board. They have to do as many as possible within four minutes. Data is recorded during this exercise only **(cf. figure 2.5A)**.

Learning Step Participants are randomly assigned either to group Classic which will perform one hour training session in CLS or group Robot which will perform 1h training in Co-RALS. During each learning session, participants have to perform two exercises: *Pea on a Peg*, *Loops and Wire* **(cf. figure 2.5)**. These two exercises are performed in a random order. They are each performed repeatedly: participants had a maximum number of five trials for each exercise. To avoid the influence of fatigue on performance, a maximum total time per exercise and a maximum time per trial is set. The exercises are the same when performed either in Co-RALS or in CLS. Exercises performed are the following:

- *Pea on a Peg*: Participants have to place 14 beads on pegs of different heights. The beads are positioned on a peg board with the cup containing them in front. A maximum time per trial of 10 minutes is set as well as a maximum number of trials of 5 and a maximum time spent on exercise of 30 minutes. Once all the beads are placed on the pegs, the trial is finished. The psychomotor skills developed are similar to those involved during *Peg Transfer*: fine motor skills, coordination, precision and depth perception **(cf. figure 2.5B)**.

- *Loops and wire*: The exercise contains a peg board with 4 loops on which is positioned a flexible wire. Participants have to insert the wire in the 4 loops in a specific order indicated on the board. A maximum time per trial of 4 minutes is set as well as a maximum number of trials of 5 and a maximum of time spent on exercise of 15 minutes. Once the wire is inserted in all the loops, the trial is finished. The psychomotor skills developed are related to depth perception and manipulation of the instruments **(cf. figure 2.5C)**.

Post-Learning Step Participants have to perform the same exercises as the one performed during the pre-learning step:

- *Peg Transfer Non Dominant*: familiarization exercise.

- *Peg Transfer Dominant*: recorded exercise.

2.4.2 Results

We present the results given by each of the measuring tools and metrics used during the experiment. As mentioned before, gaze-tracking could only be recorded for Non-Resident participants while time and score were recorded for all participants. Statistical tests were performed as a comparison between the means of each group: *Classic* and *Robot* for every metric used during *Pre-Learning*, *Learning* and *Post-Learning* steps. All sets of data were normally distributed, variances were homogeneous and samples were independent, hence Student's t tests were performed for every pair of data: number of fixations, duration of fixations, time to perform *Peg Transfer*.

2.4.2.1 Main Research Question: ***Does learning laparoscopic surgery with a comanipulated robotic assistance result in development of skills in CLS?***

Pre-Learning Step Gaze data and time data during Pre-Learning is analyzed to compare between group Classic and group Robot and make sure that there are no statistical differences between these two groups previous to the learning session. The means in terms of time taken to perform *Peg Transfer* in the Pre-Learning step are different between group Classic (3.8 ± 0.4) and group Robot (2.7 ± 0.9) but not significantly different (*Student's t Test*, t(11.2)=2.09, p = 0.06). Still, because of the low p-value, the difference in terms of time taken to perform *Peg Transfer* after learning between group Classic and Robot should be considered with caution. All other data measured before learning shows clearly no statistical difference between group Classic and group Robot in terms of gaze data *i.e.* duration of fixations during *Grab* phase (*Student's t Test*, t(8.7459)=0.62994, p = 0.5), *Transfer* phase (*Student's t Test*,t(9.4918) = -0.5219, p = 0.6) and *Drop* phase (*Student's t Test*, t(11.334) = -0.86636, p = 0.4) and number of fixations during *Grab* phase (*Student's t Test*,t(8.1897) = 0.58616, p = 0.5), *Transfer* phase (*Student's t Test*,t(8.2418) = 0.42915, p = 0.6) and *Drop* phase (*Student's t Test*, t(9.8688) = 0.54009, p = 0.6011).

These tests have been performed for Non-Resident partici-pants, Resident participants were not numerous enough to perform statistical comparisons.

Post-Learning Step

- Mean number of fixations on aimed target: **for Non-Resident participants**, before learning, on average participants perform 0.6 ± 0.1 fixations on aimed target during *Transfer* phase. In the same phase, after learning, group Classic performs 0.55 ± 0.2 fixations on average on aimed targets, and group

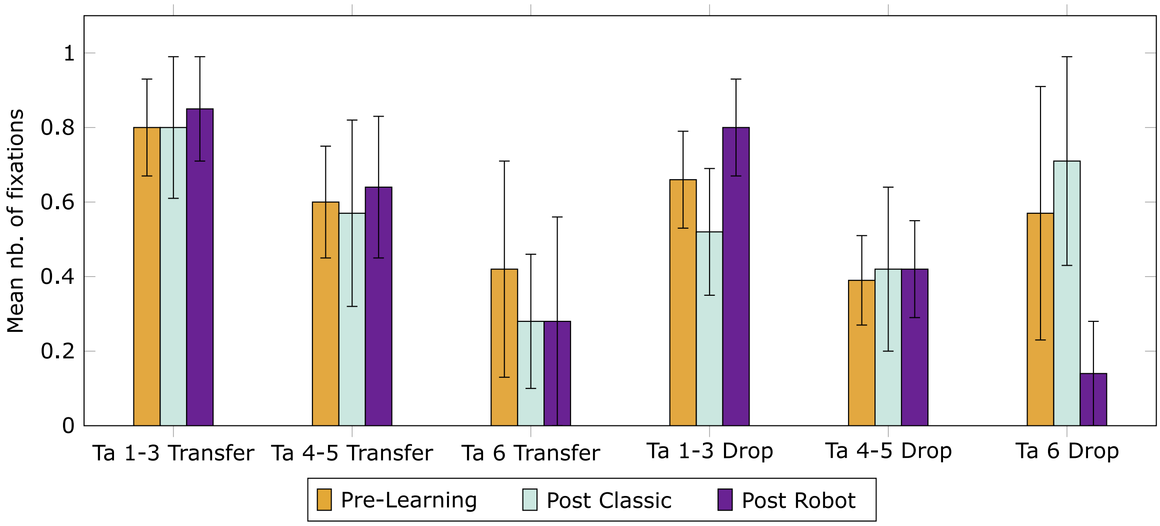


FIGURE 2.6: Number of fixations on target before reaching them with the instrument during *Transfer* and *Drop* phases: Non-Residents. **Ta1-3** (Mean number of fixations on Targets n°1, 2 and 3 before reaching them with the instrument), **Ta4-5** (Mean number of fixations on Targets n°4 and 5 before reaching them with the instrument), **Ta6** (Mean number of fixations on Target n°6 before reaching it with the instrument). Targets are separated in accordance with the % of participants who managed to reach them, this number being proportionally lower for the targets with the higher number. On average, group Robot does more fixations on targets 1 to 5 in *Transfer* phase, on targets 1 to 3 in *Drop* phase, than group Classic. Group Classic does more fixations than group Robot on target n°6, but variability is also twice as important: ±0.28 for group Classic, ±0.14 for group Robot.

Robot 0.59 ± 0.2 fixations on average on aimed target. Before learning, on average participants perform 0.54 ± 0.19 fixations on aimed target during *Drop* phase. In the same phase, after learning, group Classic performs 0.55 ± 0.22 fixations and Group Robot performs 0.45 ± 0.13 fixations on average on aimed target (**cf. figure 2.6**). These differences are not significant (*Student's t Test*, t(0.12)=20.3, p = 0.9).

- Mean fixation rate per second: **for Non-Resident participants**, the fixation rate per second decreases for both groups before and after learning all phases, except in *Grab* phase where it slightly increases for group Classic. After learning, in *Grab* phase, group Classic increases on average the fixation rate per second of 4% compared to before learning, group Robot stagnates. In *Transfer* phase, group Classic does on average as many fixations per second before and after learning, while group Robot does 5% less. Finally in *Drop* phase, group Classic decreases by 6% on average the fixation rate per second, group Robot decreases by 10% (**cf. figure 2.7**). Difference is not statistically significant between the groups (*Student's t Test*, t(1.9)=9.7, p = 0.08).

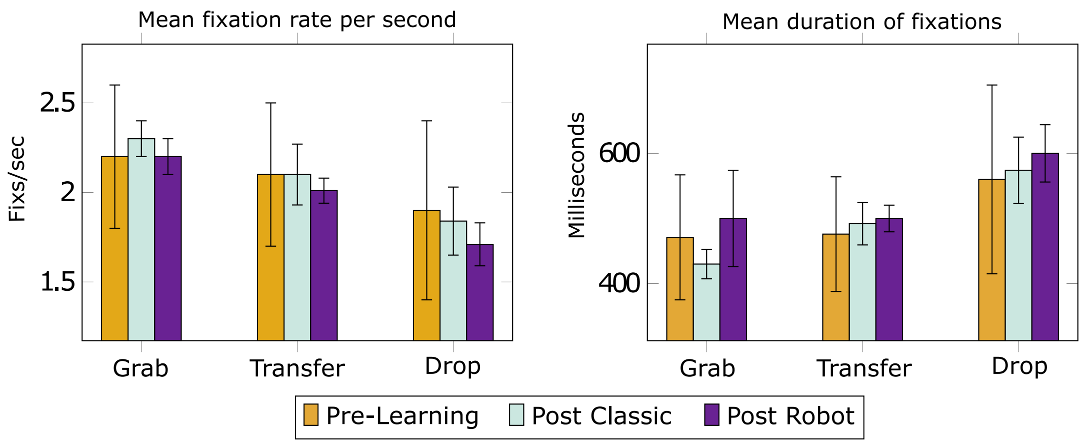


FIGURE 2.7: Mean fixation rate per second and Duration of fixations during Peg Transfer Post-Learning Session: Non-Residents. Participants in group Robot reduce the **mean fixation rate per second** in phases *Transfer* and *Drop* before and after learning while group Classic stagnates in *Transfer* phase. Standard Deviation reduces strongly for the two groups before and after learning. Participants in groups Classic and Robot augment the **mean duration of fixations** before and after learning. Standard deviation also reduces strongly for the two groups.

- Duration of fixations: **for Non-Resident participants**, the duration of fixations increases for both groups before and after learning in all phases of the *Peg Transfer* exercise, except for *Grab* phase in which it slightly decreases for group Classic. After learning, in *Grab* phase, group Classic decreases on average the duration of fixations by 9% compared to before learning, group Robot increases by 6%. In *Transfer* phase, group Classic increases the duration of fixations of 3% before and after learning, while group Robot increases by 5%. Finally in *Drop* phase, group Classic increases by 2% on average the duration of fixations, group Robot increases by 7% **(cf. figure 2.7)**. Difference is not statistically significant between the groups (*Student's t Test*, t(-0.7)=11.9, p = 0.4).

- Time to perform *Peg Transfer*: **for Non-Resident participants**, both groups decrease time to perform the *Peg Transfer* exercise after the learning session. Mean time to perform the exercise before the learning session is 3.1 ± 0.9 minutes, while mean time to perform the exercise after the learning session is, for group Classic of 2.6 ± 0.6 minutes and for group Robot of 1.9 ± 0.4 minutes **(cf figure 2.8)**. Difference is significant between group Classic (M=2.6, SD=0.23) and group Robot (M=1.9, SD=0.18), *Student t. test*, t(11.2)=2.09, p=0.05.

- Time to perform *Peg Transfer*: **for Resident participants**, both groups decrease time to perform the *Peg Transfer* exercise after the learning session. Mean time to perform the exercise before the learning session is of 3.3 ± 0.9

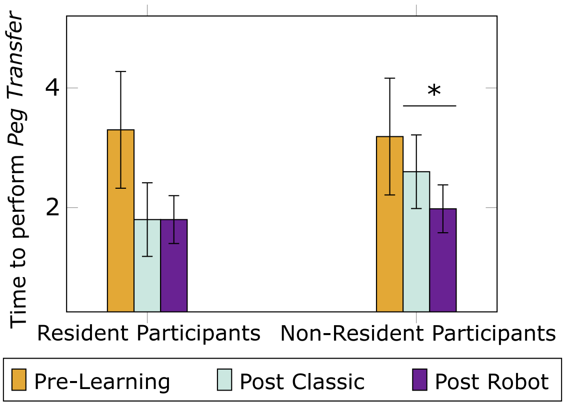


FIGURE 2.8: Mean time to perform Peg Transfer Pre and Post-Learning Session

minutes, while mean time to perform the exercise after the learning session is, for group Residents Classic of 1.8 ± 0.6 minutes and for Residents Robot of 1.8 ± 0.4 minutes **(cf figure 2.8)**.

2.4.2.2 Secondary Research Question: *Does using a comanipulated interface for RALS improve performance compared with CLS?*

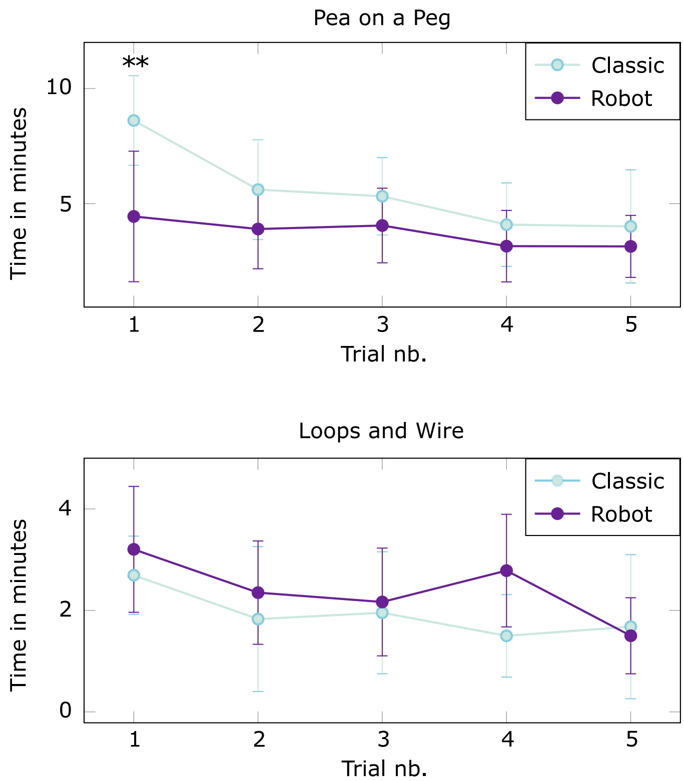


FIGURE 2.9: Learning Session Non-Residents

- Time to perform training exercises: **for Non-Resident participants**, during the learning session, for exercise *Pea on a Peg*, group Classic starts for Trial

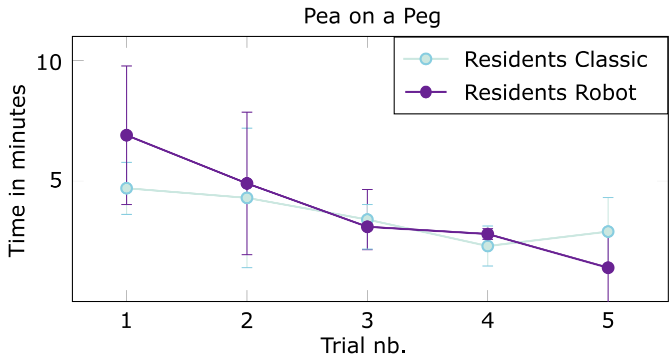


FIGURE 2.10: Learning Session Residents

n°1 with a mean time of 8.6 ± 1.9 minutes and ended for Trial n°5 with a mean time of 4 ± 2.4 minutes. Group Robot starts for Trial n°1 with a mean time of 4.4 ± 2.8 minutes and ends for Trial n°5 with a mean time of 3.1 ± 1.3 minutes. Difference of time taken across conditions is significantly different for trial n°1 at the $p < 0.002$ level [F(1,13) = 17.11, p = 0.001]. For exercise *Loops and Wire* no significant difference is observed between group Classic and group Robot. Group Classic starts for Trial n°1 with a mean time of 2.7 ± 0.7 minutes and ended for Trial n°5 with a mean time of 1.6 ± 1.4 minutes. Group Robot starts for Trial n°1 with a mean time of 3.2 ± 1.2 minutes and ends for Trial n°5 with a mean time of 1.5 ± 0.7 minutes **(cf. figure 2.10)**. After verifying the normality and sphericity of data, and the independence of samples, a repeated measures analysis of variance was performed to test for effect of learning. This effect is significant for Group Classic for exercise *Pea on a Peg* (*Anova*, F(1,6) = 63.25, p = 0.0002), but not for group Robot (*Anova*, F(1,7) = 2.215, p = 0.18). For exercise *Loops and Wire*, the effect of learning is not significant for group Classic (*Anova*, F(1,6) = 3.68, p = 0.1), but it is for group Robot (*Anova*, F(2,5)=8.4, p = 0.025).

- Time to perform training exercises: **for Resident participants**, exercise *Pea on a peg* alone is performed. Group Residents Classic starts for Trial n°1 with a mean time of 4.7 ± 1 minutes and ends for Trial n°5 with a mean time of 2.9 ± 1.4 minutes. Group Robot starts for Trial n°1 with a mean time of 6.9 ± 2.8 minutes and ends for Trial n°5 with a mean time of 1.4 ± 1.6 minutes **(cf. figure 2.10)**.

2.4.2.3 Exploratory Results: *Self perceived comfort level with the task and observed performance*

- Score for NASA TLX: **for Non-Resident participants**, they show an almost equal score for the two groups. Group Classic rates a mean score of 61 ± 6 and group Robot of 64 ± 12 **(cf. figure 2.11)**.

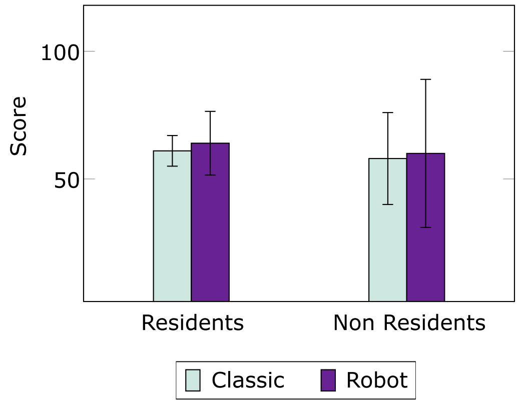


FIGURE 2.11: NASA TLX

- Score for NASA TLX: **for Resident participants**, both score very closely the task: 58 ± 18 for group Classic and 60 ± 19 for group Robot **(cf. figure 2.11**).
- Score at *Peg Transfer* exercise: **for Non-Resident participants**, mean score before the learning session for two groups is of 230 ± 81, after learning for group Classic of 163 ± 56 , and after learning for group Robot of 158 ± 56. The two groups decrease their score in a similar way, showing equivalent improvement of skills.
- Score at *Peg Transfer* exercise: **for Resident participants**, mean score before the learning session for the two groups is of 222 ± 86, after learning for group Classic of 111 ± 59, and after learning for group Robot of 147 ± 38. Group Classic decrease their score a little bit more than group Robot.

2.4.2.4 Discussion

The measuring tools' and metrics' results confirm their ability to show the differences in terms of skills and performance between the two experimental conditions (Co-RALS and CLS). They also confirm the absence of negative impact of training in Co-RALS on skills in CLS. Gaze-tracking enables to observe the subtle disparities in hand-eye coordination skills in CLS between training in Co-RALS and in CLS, although showing both train the human to perform laparoscopic surgery. Time recording showed a slightly significant difference in terms of the ability for speed in CLS for group trained in Co-RALS compared with group trained in CLS, but this result should be analyzed with care as before learning, group Robot showed better tim-wise skills than group Classic.

The scores obtained in CLS by each group show no difference in achieved performance. Time recording when performing similar repeated exercises in Co-RALS and in CLS identifies that differences in the number of repetition needed before mastering the task, and the time performance that can be achieved for each condition depends on the type of task performed. The NASA TLX, finally, confirms that no supplementary workload was felt when performing in Co-RALS compared with CLS.

2.4.2.5 Main Research Question: ***Does learning laparoscopic surgery with a comanipulated robotic assistance result in development of skills in CLS?***

Non-Resident participants Both group Classic and group Robot decrease time taken to perform the *Peg Transfer* exercise. The difference between the groups is statistically significant, with group Robot taking on average 0.7 minutes less than group Classic after the learning session. Thus, group Robot seems to have developed better time-wise skills in laparoscopic surgery compared with group Classic. Gaze patterns between the two groups are very similar. Still, group Robot makes on average, after the learning session, slightly less and longer fixations in the three phases of the exercise: *Grab, Transfer* and *Drop*. These differences are not significant, but one can postulate that longer and repetitive learning sessions would expand them.

Also, group Robot augmented, on average, the number of fixations on target before reaching it with the instrument in phases *Transfer* and *Drop* for targets n°1 to 5 while group Classic, on average, slightly decreased it, showing little improvement for the first group, and consistency for the second. We interpret these results as a consequence of having to deal with the algorithm implemented in the robot, the viscous field forcing the participants in group Robot to remain active when performing the gesture. This may have increased their attention state, despite the fact that their score is almost equivalent to that of the group Classic. In other words, the results suggest that group Robot has developed skills in laparoscopic in a way that is not statistically different to those developed by group Classic in the same task. Without it being statistically significant, group Robot even has better results in terms of number of fixations on target, fixation rate per second and mean duration of fixations after learning than group Classic.

Resident Participants Groups Classic and Robot, for Resident participants, took on average the same time to perform the *Peg Transfer* exercise after the learning session, suggesting they have equivalently improved their skills. Time taken to perform the *Peg Transfer* decreases equivalently for both group Classic and group Robot. The results from the small cohort of residents show a similar trend to that observed in the non-residents' results. This suggests that the same results could be obtained on this experiment with larger groups of residents in medicine.

2.4.2.6 Secondary Research Question: *Does using a comanipulated interface for RALS improve performance compared with CLS?*

Non-Resident Participants For Non-Resident participants, it appears that training with robotic assistance decreases the time taken to perform exercises that require precision and fine motor skills such as *Pea on a Peg*. The group of participants trained in Co-RALS took significantly less time to perform the first trial, and visibly less time to perform every other trial. Contrary to what was expected, for exercise *Loops and Wire* in which proprioceptive and instrument manipulating skills are required, comanipulated robot-assistance seems to hinder learning compared to no robotic assistance. The damping algorithm may, in this case, have disturbed the participants as it forces them to adapt to a new eye-hand coordination which has no advantage over the goal of this exercise. The implementation of an other algorithm such as virtual fixtures may help to improve performance for such an exercise but could have a negative impact on skill transfer to without robot mode. Further investigation is needed. Scores obtained at the NASA Task Load Index are very close for the two groups, not significantly different, showing an equivalent cognitive and physical load perceived when training either in CLS or in Co-RALS, suggesting it was as difficult to perform the learning session in CLS as it was in Co-RALS.

Resident Participants For Resident participants, who had a better base level at laparoscopic surgery, more trials were required in RALS for *Pea on a Peg* exercise than for Non-Resident participants to attain the same level as in CLS, but better performance was attained with the same number of trials. This may be due to the fact that, as they were used to performing in CLS, they had to re-adapt to this new setting before they could achieve their best performance on it. No significant difference was observed regarding scores obtained at the NASA Task Load Index when training either in CLS or in Co-RALS. Same as for the main question of research, a similar trend than that of the novices is observed. This paves the way for more research on effect of Co-RALS on subjects with intermediate level in CLS, to assess whether their performance can be improved significantly compared with CLS.

2.4.2.7 Exploratory Results:*Self perceived comfort level with the task and observed performance*

Non-Resident Participants. Group Classic and Robot have on average equivalently improved their score at the *Peg Transfer* exercise before and after learning, with group Robot slightly better than group Classic. The mean score given at the NASA TLX is almost equivalent for the two groups, showing no superior workload for group Robot compared with group Classic.

Resident Participants. Resident participants started with a score equivalent to the Non-Resident participants -222 compared with 230- and ended with a slightly better score than the Non-Resident participants -111 compared with 153 for group Classic and 147 compared with 158 for group Robot-. No difference is observed in terms of perceived workload between group Robot and group Classic: the mean score at the NASA TLX is very close for the two groups.

2.5 Conclusion

The experiment conducted and its results, first, demonstrate that the measuring tools and metrics used and the exercises performed succeed in showing the learning process and performance of participants on tasks of robotic and classic laparoscopic surgery. The different metrics' results also indicate the advantages and limits of Co-RALS for learning. A comanipulated interface for RALS seems to succeed in maintaining active learning of the motor skills of the user *i.e.* in the *target task* (CLS) while performing the robot-assisted task (Co-RALS), contrarily to what was observed by Blavier et al. with the da Vinci [19; 20]. However, these results confirm the motivations that lead to the development of comanipulation [109]: to support and assist the gesture to make it easier to perform without changing its characteristics. Gaze-tracking and time recording permit observation of two different aspects of the learning process: the psycho-motor skills' acquisition and the immediately visible performance. These two measuring tools taken together provide a comprehensive overview of what has been learned when training with robotic assistance. However, they go along with other measurements, whose purpose is to study the performance of the human-robot team.

Thus, to evaluate the learning curve on exercises of laparoscopy either when training in Co-RALS or in CLS, we used time-recording also. We observed the learning curve of two exercises: one is learned faster and performed more rapidly in Co-RALS than in CLS, and the other is learned and performed more slowly with the robot compared to without. Hence, the superiority of the human-robot team's performance in terms of the learning curve, seems to depend greatly on the type of exercise performed. Co-RALS enables to increase performance for exercises of fine motor skills and precision but for a task of proprioceptive and manipulating skills, *Loops and Wire*, it does not improve the learning process. The exploratory measures show other aspects of the human-robot interaction. The results obtained with the NASA TLX suggest that interacting with a robotic assistance to laparoscopic surgery results in an equivalent workload compared with performing CLS. The comparison of the peg transfer scores in CLS either after training in Co-RALS or in CLS demonstrate and equivalent performance between the two groups, confirming the previous results.

This study encourages to pursue research in human-robot interaction using quantitative metrics to qualify the conditions for interactions to be virtuous both for the human, and for the human-robot team's performance. The results are also in favor of other interaction designs for RALS than the dominant one, Tele-RALS. Still, these findings present some limitations. First, the number of exercises performed are limited. Future research on comanipulated interfaces and RALS with longer, more complex and realistic tasks may show more clearly how it can benefit to students in surgery. Second, the number of Resident participants is small. A study with a greater number of Resident participants, with groups of different levels would show more precisely how the comanipulated robotic system impacts performance and develops psychomotor skills depending on the level in CLS. Also, our study only focuses on one aspect of laparoscopic surgery which is dexterity. One could imagine future research that would involve knowledge also: of anatomical structures, procedures, risks etc. Despite these limitations, our results pledge for more research on human-robot collaboration, which could lead to more adapted and hence more easily adopted technologies.

2.6 Contributions of the chapter

In this chapter, we present interaction designs for robot-assisted surgery today. One type of surgical robotics, comanipulated, is studied in greater details. On the basis of what is stated about comanipulation, a study is described on the way a comanipulated surgical robot, which integrates in its development both dimensions of surgical learning and of surgical performance may contribute to the hand-eye coordination learning of technical surgical skills and how it may even enhance this learning. Beyond the demonstration of the fact that training on a surgical robot can teach to perform surgery without it, the overall aim of the study is to show that integrating a user's needs and constraints (such as the necessity to learn traditional surgical skills) in the design of a surgical robot can have direct effects on reducing some of the difficulties encountered by medical residents when training for surgery.

Still, it is important to emphasize that although this posture is interesting to adopt when developing surgical robots, many of the skills needed to master surgery cannot be acquired using a surgical robot. A surgical robot has a strong and valuable capacity to make gestures more precise, less tiring, more secure, but no capacity to train neither novices nor experts on the knowledge that makes this gestures possible. In the words of Lucile Vadcard, a researcher who works on didactics of technical gestures in the context of health, *Paradoxically, the gesture depends on the individual's knowledge at the same time as it enables to develop and structure it.* The important thing to remember here is that a technical gesture can only exist if structured by *knowledge on the environment and its properties, in relation with the purpose of the activity and the individual's physical abilities* [162] and that this knowledge is not, and can never be, taught by the robot. This observation then invites to the development of technological learning tools by building on pedagogical and didactical considerations, which can even result in the finding of the continuum between these technologies, rather than their individual advantages. Lastly, it invites to teach this knowledge in a way that is consistent with the expectations, needs, and constraints of medical residents.

Chapter 3

Video-based learning, pedagogy and surgical education

This chapter presents the state of the art in terms of pedagogy and video-based surgical learning, exposes the existing knowledge representations in surgery, and introduces a second study. The study is exploratory. It aims at investigating both the concrete difficulties faced by medical residents in their surgical training, their consequences, and the ability of a training video based on human learning theories and model to diminish these difficulties. Using the methodology of the interview, and the testimonies of the participating medical residents, answers are sought as to the creation of an association between the knowledge captured and exposed in the video (*i.e.* the scripting of the video) and the reduction of the obstacles faced to gain proficiency in surgery.

3.1 State of the art

3.1.1 Video-based learning and pedagogy

Video-based learning has the capacity to bring knowledge to many people concurrently without requiring a heavy infrastructure or burdening healthcare [5; 110], but studies on this matter in surgical education have so far focused on the display of video content, but less so in their creation. Even thought this has aroused little attention in the field of surgical training, in other domains some studies show video-based training, when supported by theories of human learning [120; 53] and multimedia design principle [142], has the most value. In this thesis, we argue that video-based learning tools are not efficient as the content they use is rather demonstrational than pedagogical, mainly focusing on non-technical skills, lacking multimedia design principles [142], and consideration for learning theories [132]. Furthermore, these videos do not provide learners with the implicit and tacit rules acquired during years of surgical practice and which constitute the surgical know-how [99].

Quite recently, research studies have pointed out the importance of the integration of research-based theories of human learning and evidence-based principles for the design of effective instruction in surgical education [102; 27].

In a book entirely dedicated to Video Research in the Learning Sciences by Sharon J. Derry et al. [34], the authors address *"4 challenges for scientists who collect and use video records to conduct research in and on complex learning environments:"*

- (a) Selection: How can researchers be systematic in deciding which elements of a complex environment or extensive video corpus to select for study?
- (b) Analysis: What analytical frameworks and practices are appropriate for given research problems?
- (c) Technology: What technologies are available and what new tools must be developed to support collecting, archiving, analyzing, reporting, and collaboratively sharing video?
- (d) Ethics: How can research protocols encourage broad video sharing and reuse while adequately protecting the rights of research participants who are recorded?

These challenges are addressed to all researchers whose research topic is video learning but they are particularly relevant in the case of video learning for surgical education. The **selection** process then refers to the identification of a framework, which would address the challenges of how to compile and arrange video footage to formalize elements that are transversal to different surgeries and that are essential for the surgical student at the different stages of his/her learning process. This is a very important matter. We partially address it during this thesis. The **analysis** refers to the selection of human learning theories and models that apply to surgical learning. This is the challenge that is addressed in the experimentation presented in this chapter. The **technology** refers to the informed choice in terms of technology to record and display these learning videos, this challenge is addressed in the next chapter. Finally, the **ethics** is particularly challenging in surgical education as surgical videos filmed in the OR represent patients who are filmed while receiving care, in a highly vulnerable position. Also, the videos show a very intimate aspect of their lives. This challenge is also a very important one but we were not able to completely address it during this thesis. Still, we did obtain a favorable opinion from the ethics committee (No. CER-2021-073) of Sorbonne Université.

3.1.2 The complex knowledge representation

There is an obvious need for better knowledge representation in surgery: only little work have recently focused on the identification of the psycho-motor skills required in surgery. Yet, it is known that there are three stages that occur during the acquisition of a motor skill: the first stage (cognition) is an understanding of the task: individuals who are provided with a clear description and a demonstration of the task are more likely to master a new skill than those who are not. The second stage (integration) is the moment where motor skills unique to the task are applied to avoid inefficient movements. In the final stage (automation), the skill becomes automatic so that there is no need to think about each step or rely on external cues [81].

The moment of automation, which underpins technical competence, is the moment where a map exists of the whole performance in the neural circuits. At this moment, it becomes difficult for experts to explain or demonstrate the components of the task to others. Thus, the skills of an expert surgeon are not easy to identify and complex actions may be difficult to break into understandable component parts. Still, for surgery to be taught efficiently, these need to be defined [77]. One way of identifying and dividing surgical gestures is the computer-based approach: where surgical gestures are defined as simplified, formal, or semiformal representations of a network of surgery-related activities, reflecting a predefined subset of interest [113].

3.1.3 The computer-based approaches

Widely used approaches to representing surgical procedures are Computer Interpretable Guidelines (CIG) and Surgical Process Models (SPM).

CIGs represent medical knowledge to be shared across medical institutions for the purpose of standardization of clinical practice [31].

CIGs are designed for representing and communicating how a procedure should be properly carried out therefore they do represent effects of incorrectly performed actions, which is essential for teaching purposes. Surgical Process Models represent operational activities related to surgical resources, e.g., time and operators [85; 97; 112; 113]. SPMs typically represent the hierarchical tasks in a surgical procedure, from the high-level actions to the low-level motor movements. Like CIGs, SPMs focus on the correct activities in a procedure and do not include effects of incorrectly chosen or executed actions. In the words of Lalys et al. [85] in their literature review, in an SPM:

"The highest level is the procedure itself. The procedure is composed of a list of phases. A phase is defined as the major types of events occurring during surgery. Each phase is composed of several steps. A step is considered to be a sequence of activities used to achieve a surgical objective. An activity is defined as a physical task and each activity is composed of a list of motions. The motion can be considered to be a surgical task involving only one hand trajectory but with no semantics. One assumption is that each granularity level describes the surgical procedure as a sequential list of events, except for the surgical procedure itself and for lower levels where information may be continuous."

However such approaches do not include elements related with learning, such as the teaching of decision making by instructors, the teaching strategies used, the rationale behind these strategies and the knowledge that the instructors bring with them to the teaching. These approaches do not model the learner but the expert. An ITS that is designed for surgical education is SDMentor, created for teaching decision making in the preoperative and intraoperative stages of root canal treatment [163]. Two essential components of this ITS are teaching strategies and knowledge representation requirements. It aims at representing surgical decision making, which requires an understanding of the causal relations in the surgical domains. They are a function of how actions are performed, the effects of previous actions, and the condition of the patient. This requires continuous situation awareness to assess patient state and the effects of previous actions. It captures actions with parameters and conditional effects, changes in the state of the patient, and the situation awareness process of interpreting observable parameters. The pedagogical model makes use of this representation to respond to students errors and to explore the students knowledge. The teaching strategies and knowledge representation requirements are identified through experts interviewing and observations.

Surgical activity representation in the domain of surgical education has also been studied using the TELEOS system [93; 95; 157; 158], a simulation-based intelligent tutoring system (ITS) for the learning of percutaneous orthopedic surgery. It is based on a model of human learning, the cKç model by Balacheff [15] which we describe later on in the thesis 4. This model can formalize the conceptions of an expert but also of a learner that can be misused in a domain and thus lead to errors. This computer environment includes a set of *problems*, defined according to the their didactic variables (an element whose involvement affects the outcome of the problem in question), a set of *operators* which are the actions that the user has the ability to perform while solving the problem and a set of *controls* defined in the form of "if...then" or predicates (statements). A mapping of the three sets is then established. The focus is on perceptual-gestural knowledge. The system produces a trail of the student's problem-solving activity and uses Bayesian networks to diagnose the activity. A didactic decision agent uses the diagnosis to generate feedback to the student.

To be able to describe all these elements of a surgical procedure, it is not enough to be an expert in the procedure or to have seen many of them. A meticulous work of literature reading on surgical interventions, experts interviewing, observations in the OR must be carried.

3.1.4 Qualitative methods for surgical learning research

Here, we describe qualitative methods we use in the study presented later on, for different purposes. Qualitative methods were used to help model surgical procedures (*i.e.* the C-Section and hysterectomy), and to investigate what links pedagogy, video-based learning and surgical education.

3.1.4.1 Interviews

In social sciences, interviews are a method of data collection designed to elicit information from interview participants. They are especially useful when the topic of research is complex and requires long explanations, subtlety and needs a conversation to be clarified. They are also an appropriate research method in the case of the study of a process.

Interviews can either be perceived as a way to access authentically and directly the interviewees' realities [10; 147], or as a scene where the interviewers and the interviewee co-construct data for a research project, as advocated by Holstein and Gubrium. They are two sociologists who have published important and exhaustive work on the interview as a research method. They claim that "that all interviews are reality-constructing, meaning-making occasions, whether recognized or not" [59]. To apprehend interview as a co-construction is to attempt to create an analytical, dialogic (that refers to the use of conversation or shared dialogue to explore the meaning of something, as opposed to monologic, which refers to one entity with all the information simply giving it to others without exploration and clarification of meaning through discussion), and compassionate ethic with interviewees [41].

In the words of Carolyn Ellis and Chris J. Patti, two professors of communication whose research interests are personal and collective storytelling, and compassionate communication: "*[Co-constructed interviewing] aspires to understand and treat conversational partners not as traditional "participants," but rather as collaborators in at least three ways: (i) that sharing in dialogic/discursive authority and expertise on the subjects at hand and in the trajectories, flows, and topics of the conversation is desired; (ii) that the interviewer's motivation is to have a constructive conversation that is open to the worldviews of interviewees, and that the roles of interviewer/interviewee can and sometimes do reverse and become blurred; and (iii) that interviewers continuously consider the ethical consequences of such research relationships and motivations, in addition to the potential pitfalls of attempts to collaboratively represent such results.*" [119].

As mentioned before, in some of the works conducted in this thesis, we have performed interviews. While this compassionate approach applies particularly well to emotionally charged research topics such as those studied by Carolyn Ellis and Chris J. Patti, we believe that their guidelines are valuable tools to use in the conduct of an interview, even for less emotionally charged research subjects such as video-based surgical learning. We have sought proposals for answers to the question of how pedagogy, videos, and surgical learning link together on the basis of the assumption that an interview is a construction, and in the dialogue between the interviewer and the interviewee.

3.1.4.2 Observations in operating room

Different work in the fields of anthropology, education sciences, and human-computer interactions have used observations in the OR as a tool to study, investigate the impact of the introduction of telemanipulated surgical robot [12; 122; 23], the hierarchical relations between the different actors [127] or for the same purpose as our, the impact of human learning theories for the creation of surgical training [99].

"In the narrowest and most determined sense, observation consists in being present and involved in a social situation in order to record and interpret it, while striving not to modify it. This social situation is always the product of an interaction between the participants themselves and, in one way or another, between the participants and the observer; it takes the form of events composed of successive sequences with a beginning and an end. A one-time observation consists of a visit or two to the site for a simple exercise, scouting or first attempt. A systematic observation is one that is repeated, following a concerted schedule" [170].

Observation is a means of recording the behavioral activity of participants, which cannot be translated into words.

In a case that is of particular interest to us, observations were used to elicit the automatised, untold *reasons* behind the surgical gestures in orthopedics surgery [161]. These *reasons* had been identified as essential for the learner of the basis of a human learning model cited before in the thesis, the cKç model [13]. The observations enabled the identification of validations, actions, verifications, and controls related to illosacral screwing and which were not found neither in the scientific nor during interviews with experts. It is the same approach that we have carried out in the following experiment.

3.2 Our approach: Learning theories and video-based surgical learning

3.2.1 Background

In the following experiment, we present an approach that differs from those previously presented for surgical education. Unlike computer-based approaches, we propose a rather low-technology solution: a video for surgical training developed using the classification system of a human learning model. The video serves as training for a basic procedure in gynecological surgery, the hysterectomy (the removal of the uterus). The video is visualized by residents in medicine specialized in gynecology: some of them have already performed parts of the procedure when viewing the video for the first time, and others have not. They have all seen hysterectomies before. All perform, during their current internship as a resident, some gestures presented in the video when participating in other interventions in gynecology such as the C-Section. Some of them take part in hysterectomies during the training which consists in visualizing the video, as part of their current internship.

The investigation presented through this experiment focuses on the investigation of the difficulties faced by the medical residents when trying to train for surgery, as well as their consequences. The investigation is also focused on the ability of the video-based training presented in the experiment, whose creation and scripting is directly based on a pedagogical theoretical framework, to diminish these difficulties. These difficulties have already been discussed in this thesis, such as the fact that time spent in the Operating Room (OR) is shortening due to working hours restrictions and the augmentation of the number of students, the fact that generally speaking surgical training are too technology-oriented and do not consider the learners' needs and previous knowledge, and finally that they do not rely in their creation on human learning theories. These materials, while designed to export clinical learning outside the clinic, fail in covering many aspects of the surgical learning process which is long and complex in the sense that it requires to master and combine various technical, as well as non-technical skills.

The experimentation we carried out with this video and its use and appreciation by the medical interns, impact on their knowledge and skills, is original with respect to the experiments generally conducted in the domain of surgical education. Considering the subtlety, the complexity of the effects sought and the fact that they depend strongly on each individual, the methodology used to seek for answers to the questions of research is that of the interview. Before presenting the results obtained from the interviews with the medical residents on the training video, we present the human learning model that led to the video creation.

3.2.2 Conceptual fields theory

In this chapter, we approach pedagogy through the theoretical framework of constructivism. Constructivism is often defined in opposition to behaviorism [55], considering cognitive development as a construction of active learner reorganizations and not as a linear process, being the result of maturation and stages [47]. Learning in this theory is interpretive, recursive and a non-linear building process of constructing meaning, as active learners interact with their surrounds, the physical and social world. Having difficulties with meaning making engenders progressive shifts in perspectives that can be generalized across experiences and that often require the undoing or re-organization of earlier conceptions [47]. These generalizations are called OPERATIVE INVARIANT. Derived from this theory in the field of psychology, is the conceptual fields theory by G. Vergnaud [165], whose concepts are illustrated in Figure 3.1 and Figure 3.2.

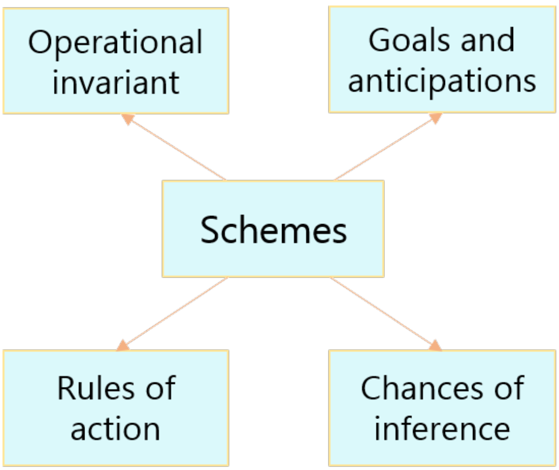


FIGURE 3.1: Schemes in the conceptual fields theory

According to G. Vergnaud, *"The theory of conceptual fields is a cognitivist theory which aims at providing a coherent framework and some basic principles for the study of the development and learning of complex skills, especially those related to science and techniques"* [164]. The conceptual fields theory presents the relations between explicit knowledge and implicit OPERATIONAL INVARIANTS that partially constitute schemes [165].

Schemes are, according to Vergnaud, the cognitive activity which is very closely linked with the visible activity of the subject performing a gesture. A scheme is composed of up to four categories of elements: *goals and anticipations*, *rules of action*, possibilities of *inference in a situation*, and *operative invariants*. The function of schemes is *"to organize and generate the activity in situation"*, and schemes are both *"producers and products"* [167]. The learner has to be able to represent given situations in a conceptual field, and either activate a relevant scheme to solve the problem caused by this situation, or *"map this situation into a symbolic representation and then operate inside this representation until the solution is reached"* [165].

The OPERATIVE INVARIANTS represent the key elements of the model since they are used to select and interpret the relevant information to solve the problems that individuals face in complex situations, such as surgery. The OPERATIVE INVARIANTS that partially constitute the schemes allow the subject to capture, select and integrate the information present in a situation and to process it thanks to the categories of thought that they have developed.

The conceptual fields theory has been used before in the domain of surgical education to describe the reasoning behind the surgeon's actions [161], or as a basis for the creation of a simulation-based intelligent tutoring system (ITS) for the learning of percutaneous orthopedic surgery, the TELEOS system [93; 95]. As reference for the development of TELEOS, the conceptual fields theory enabled to better understand and identify the structuring points of professional expertise in the surgical activity of sacroiliac screwing, a specific surgical procedure. It also allowed to better understand how certain sensory-motor patterns are acquired and to define and experiment later on some of their learning conditions.

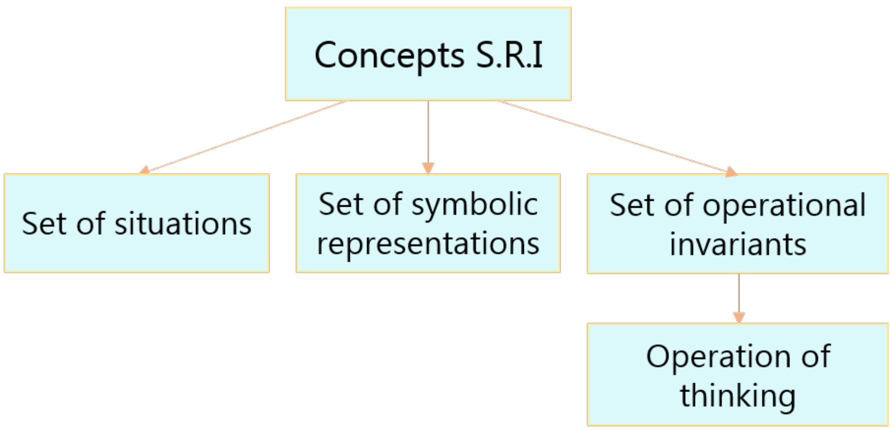


FIGURE 3.2: Concepts in the conceptual fields theory

Thus, we hypothesize that using this theory as a framework to create a pedagogical video for learning hysterectomy by laparotomy is relevant as it enables to identify and define the explicit and implicit knowledge necessary to attain proficiency in this procedure, and provides the key to understanding how to expose this knowledge to attending surgeons as well as how learning of the surgical procedure occurs during guided practice.

3.2.3 Methods

3.2.3.1 Model of the surgical intervention

To build the model, we observed 6 different videos of hysterectomies, we directly observed 15 hysterectomies, read literature on hysterectomy [150; 26; 78; 80], we performed interviews with 2 surgical experts on hysterectomy and one medical resident in gynecology obstetrics. We build a model of hysterectomy by laparotomy with six different classes, directly derived from Vergnaud's conceptual fields theory. We only make a partial use of the model, leaving aside the *inferences* in situation which are the reasoning to 'calculate' the rules and expectations [166]. We consider that these inferences are calculations made by the learner when performing the target ACTIVITY and are therefore difficult to represent in the video and/or to generate using the video.

These classes used to model the hysterectomy by laparotomy are the following:

- ACTIVITY: The surgical steps of hysterectomy by laparotomy, from which are derived the *actions, goals* and *anticipations*.

ACTIVITY is organized in an identical way for a given class of situations by schemes. Schemes are constituted by the following four categories of the model:

- ACTIONS, GOALS and ANTICIPATIONS: the surgical gestures to be performed to fulfil the objectives of the ACTIVITY, from general to specific, including the expected results of these gestures.
- RULES OF ACTION, INFORMATION GATHERING and CONTROLS: A *rule of action* is a rule which result conditions how the surgical actions are performed, depending on the value of different variables in the situation. *Information gathering* and *controls* are the actions of verifying the state of the world to identify the values of the different variables in the situation, at each step of the hysterectomy by laparotomy.
- OPERATIONAL INVARIANTS: Concepts, given meaning through different kinds of situations, each of which partially deconstructs the concept as dependent on a single situation and integrate it in a conceptual field that includes various different situations for the same concept. In the case of hysterectomy by laparotomy, concepts are knowledge that are considered true in certain situations, depending on the results of the RULES OF ACTION and depending on the ACTIVITY being performed.

Activity	Actions, goals and anticipations	Rules of action, Information gathering and controls	Operative invariant
6. Bladder detach-ment	1. Mobilize the bladder: begin mobilization at the midline of the cervix	**Before mobilizing the bladder, palpate the cervix from the anterior and posterior sides.** If you palpate the cervix, then this will allow you to check its position	Before mobilizing the bladder, the surgeon should palpate the cervix from the anterior and posterior sides of the uterus to check its position. It frequently drifts laterally due to fibroids or adhesions. Palpation is also essential to estimate the cervical length. Second, mobilizing the bladder prevents bleeding from the lateral vesico-uterine ligaments.
6. Bladder detach-ment	2. Lift the anterior leaflet of the severed broad ligament		When the surgeon lifts the anterior layer of the broad ligament, the vesico-uterine space opens spontaneously where the first incision should be made, in the center of the cervix.
6. Bladder detach-ment	3. Push the scissors vertically to the cervix and cut the connective tissue	**Identify Halban's fascia.** If you push the scissors vertically at the cervix and cut the connective tissue, then this will reveal Halban's fascia. **Check for fat**. If you encounter fat, then change the route. Encountering fat means the dissection coming too close to the bladder.	Halban fascia is white, soft and shiny. The fat belongs to the bladder. Its presence indicates that you are not in the right plan.

TABLE 3.1: Activity No. 6 and its related ACTIONS, GOALS AND ANTICIPATIONS, RULES OF ACTION and *Operative Invariant*

Finally, the last element of the model is:

- THE INTERVENTION DOMAIN: the situation in which the constituent elements of the scheme specifically apply, situation which can be as general as the surgical intervention, or as specific as the result of a RULE OF ACTION.

Through our empirical work of observation, conversation and investigation, we settled on 9 *activities*: 1. Positioning of patient, 2. Incision and inspection, 3. Opening of the peritoneum and exposure of the round ligament, 4. Opening of the broad ligament, 5. Ureter identification and section of the lumbo-ovarian, 6. Bladder detachment, 7. Ligation and section of the uterine pedicles, 8. Vaginal opening, 9. Closure of the abdomen. The full model with all the activities can be found Appendix A, we provide an excerpt detailing activity No.6 in Table 3.1.

3.2.3.2 The video

The editing of the video is done on the basis of the elements of the model. The video displays images of a total hysterectomy by laparotomy and are captured in the Operating Room (OR) as can be seen on Figure 3.3. The films obtained in the OR are edited to represent the *activities* which represent most of the chapters in the video (seen on Figure 3.3, **A**) but not all of them. Some chapters concern *rules of action* or an *operative invariant*. The first example of a chapter in the video is **Positionning of the patient** on Figure 3.3. Audio comments describe the *actions, goals and anticipations*, as well as the *rules of action* and the *operative invariant*, they are activated or inactivated by clicking on Figure 3.3, **B**. The *actions, goals, anticipations, rules of action* and *operative invariant* are sometimes made more explicit with text written on the images such as in Figure 3.3, **C**: **Opening of the anterior leaf of the broad ligament**, or anatomy boards and drawings such as in Figure 3.3, **D** and **E**: **Ureter identification** and **Bladder detachment**, to explicitly show the action to be performed, as well as the underlying anatomical structures which can be injured when performing an action.

3.2.3.3 The participants

Participants are seven 1st year Residents, specialized in gynecology obstetrics. As can be seen in Figure 3.4, participants each have a different experience with hysterectomies, some have seen only one or two before starting the video-based training, and others have seen four of five. During visualization of the video, the experience also differs: some can make an immediate connection between the video and actual practice because they take part in hysterectomies during the current internship, and others cannot. The fact that all the participants do not have the same level, as we shall see, enables to observe important elements, on the one hand in the way this video is understood by the participants and on the other hand in the way surgical learning occurs, and where the difficulties lie.

3.2.3.4 Procedures

Each participant was interviewed two times, at two weeks interval. In between the two interviews, the participants were invited to visualize the learning video, as many times as they wanted. The participants amount of knowledge on the procedure and their experience of performing the procedure before training with the video differs greatly. Each interview lasts between 15 and 25 minutes. They are performed by two researchers. In line with the methodology for interviewing mentioned above, interviews are co-constructed interviews, in an analytical, dialogic and compassionate manner. We consider that interviews are not only a way of

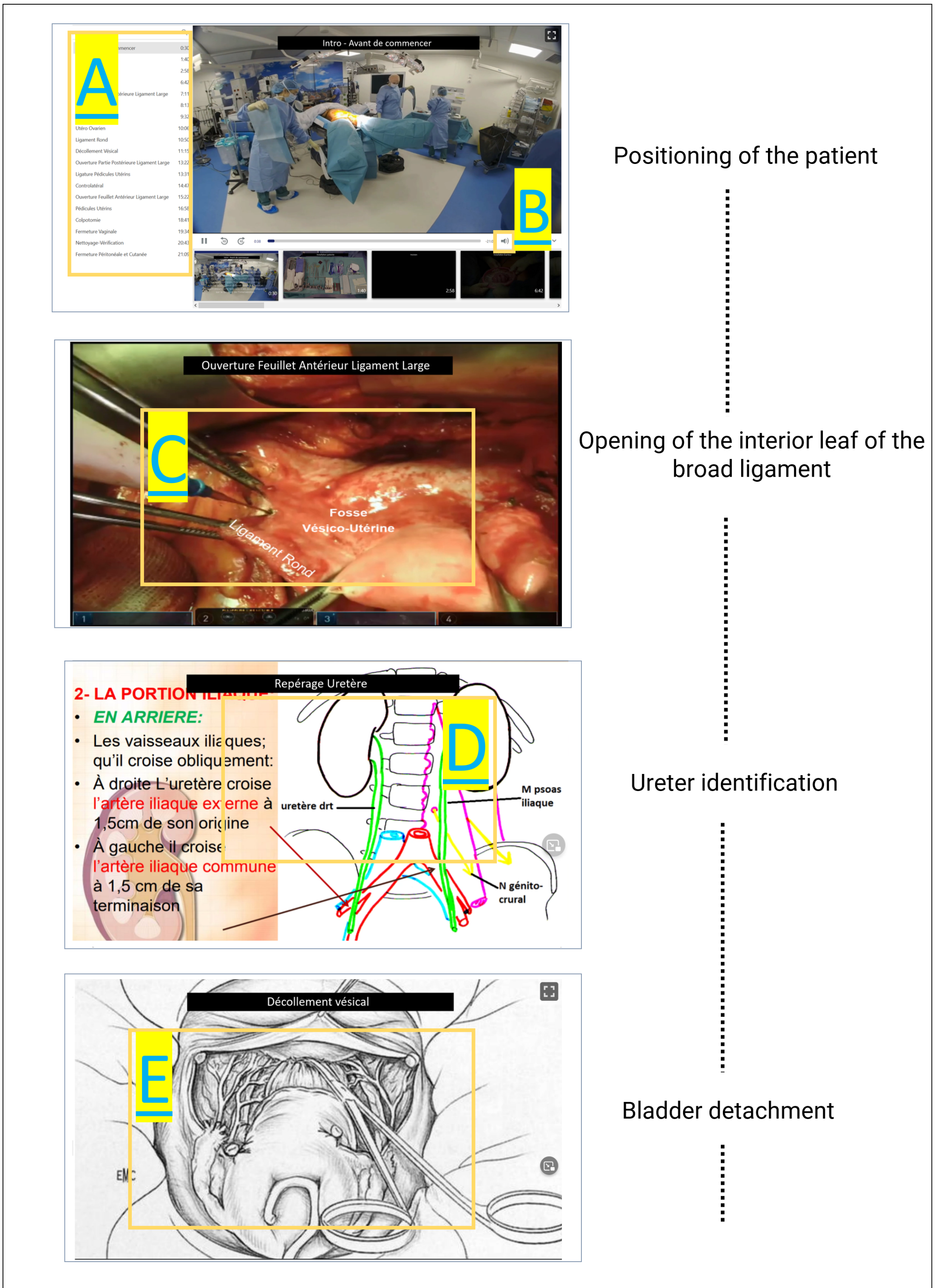
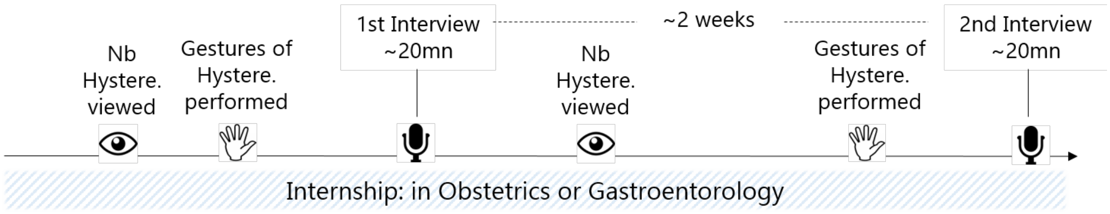


FIGURE 3.3: Open hysterectomy video: 1. Introduction, 2. Opening of the anterior leaf of the broad ligament, 3. Ureter identification, 4. bladder detachment. The learner can navigate between the different *activities* of the intervention by clicking on the chapters displayed on the left side of the screen (A), or on the lower part of the screen. Audio comments (B) synchronized with the images of the intervention describe the *Intervention domain, Actions, goals and anticipations, Rules of action*, and *Operative invariant*. Text appears on the images (C) the show the hidden anatomical structures mentioned in *rules of action* and *operative invariant*. Anatomical boards (D) and explanatory drawing (E) show the actions to be performed and anatomical structures mentioned in *rules of action* and *operative invariant*.



P7	5	Y	2	Y
P3	2	Y	1	Y
P6	4	Y	0	N
P1	3	Y	0	N
P2	3	N	0	N
P5	2	N	0	N
P4	1	N	0	N

FIGURE 3.4: Number of hysterectomies viewed for each participant before the first interview and between the first and the second interview, gestures of hysterectomy performed before the first interview (Y/N) and between the first and the second interview (Y/N), for each participant.

accessing a truth that exists without them, but are also reality-constructing. Thus, we perform a *constructivist* analysis of the interviews.

The interviewers remain open to interviewees views and topics of conversation desired. Interviewers are learning from the interviewees. Still, themes of interest to the interviewers were chosen to be addressed and examples of associated questions were prepared, for each interview: before viewing the video, which can be found in Appendix B and after viewing the video, which can be found in Appendix C. The themes to be addressed during the interviews were the following: 1. Before viewing the video: **participants experience with surgery in general and hysterectomy in particular**; **knowledge of hysterectomy; examples of moments viewing hysterectomies or participating to hysterectomies; training received on hysterectomy**; **shortages felt in surgical education; suggestions to overcome these shortages** and 2. After viewing the video: **experience with hysterectomy since the first interview**; **training on hysterectomy since the first interview**; **moments of association between video and hysterectomy viewed or performed; general opinion on the video**; **observed difference between the video and training generally received**. In between the interviews, the participants were able to visualize the video as many times as they wanted. They had access to the video through a URL.

3.2.4 Thematic analysis results

We have identified one overarching theme: *the complementarity and influence of the OR on the video* and four sub-themes: the fact that *Practice gives learning a meaning and necessity*, that *The best learning scenario lies in the repeated succession of the pedagogical video and practice*, that *Acquiring knowledge with the* *pedagogical video results in a greater feeling of belonging* and the last sub-theme, *The video and the creation of operating constants.*

3.2.4.1 Practice gives learning a meaning and necessity

The proximity of the video with practice appears to be an essential component of learning in two ways: 1. the video has to show the reality in all its complexity otherwise the mental representation is impossible. 2. The knowledge presented in the video must be put into practice to make sense.

About the necessary proximity of the video with reality, **R5**, who has never participated in a hysterectomy but who has seen two, says:

"We can't visualize until we see in pictures what to expect. What does it represent and how is it done?" **(R5)**.

As cited earlier in the thesis, there are many ways to train for surgery outside of the OR: there exists simulators for surgery, as well as manuals, manikins, Virtual Reality (VR) and Augmented Reality (AR) scenarios. Yet, very few of these use real images of the OR and therefore fail to make the connection in the medical residents' mind between the *theory* and the *practice*, *i.e.* between the information they give and the gestures performed by the experts in the OR.

About the realism of the video, and the absence of realism of other learning material, **R3** who has seen and participated in several hysterectomies mentions:

"You visualize things better. Yes, you understand better. You visualize better what's going on than when you just have a text where they tell you that they're going to dissect your ligament and then you don't even really know exactly what the ligament looks like. Because you've been told that it's inserted at such and such a place. But if you can't see it with your eyes, it's complicated." **(R3)**.

As said before, gesture learning is a paradox: it depends from the individual's knowledge at the same time as it develops and structures this knowledge. This paradox is directly observed in the interviews conducted with the residents in medicine. This is particularly noticeable in the words of **R4**, who has only seen one emergency hysterectomy before participating in the video-based training. Because of the urgency and the severity of this specific procedure, s/he could not develop a mental representation of the intervention: its steps, the anatomical structures, the instruments used, the risks... Furthermore, the first hysterectomy seen was in laparoscopy while in the video the hysterectomy is in laparotomy. About the fact that the knowledge presented in the video must be put into practice to make sense and to be structured, the words of **R4** give valuable information. After viewing the video one time, **R4** mentions:

"I would say that I had a little trouble with this video" (**R4**)

and then to explain the difficulties faced with the video:

"So I think that the next 6 months, no, I won't really do [a hysterectomy] [...]. This is not the right time for me. (**R4**) *That's probably not the priority here, the hysterectomy."* (**R4**)

and also:

"Psychologically, I was expecting a laparoscopy. So I found the laparotomy aspect quite disturbing. And the view was not what I expected." (**R4**)

The video was too far from the OR practice for this participant to be even just listened to and entirely visualized. Yet it was designed to be accessible and instructive. Still, **R4** is not going to participate in any hysterectomy during her current internship, and so the knowledge given in the video is not needed, neither can it be structured, *i.e.* given a meaning. Practice is learning, performing the gesture also means learning the reasons behind the performance of this gesture. **R4** mentions not having neither the time nor the need to learn about hysterectomy by laparotomy, but the fact that s/he does not practices also means that there is an entire part of knowledge, the one acquired through practice, to which s/he does not have access.

Beyond the fact that practice gives meaning, there is another essential aspect that it also provides: the need to learn. We mentioned several times before the importance of taking into consideration the needs of medical residents, and this participant's testimony is a representation of this importance: his/her need is not to be trained on hysterectomy and even less by laparotomy so s/he has no time to spend on this video, as informative as it may be. **R4** says it in in very explicit way:

"[...]spontaneously the brain gets rid of all this useless information and if it's not in concordance with what you're going to do in the internship it's not very interesting, right away" (**R4**).

Residents have a busy schedule, they cannot offer to learn gestures that they do not practice every day as their heads are already full with the gestures they practice every day and are trying to learn. A video-based training, or any training, must come at the right time according to the daily practice and the needs of the medical residents. When a video-based training meets both of these conditions, is when the video interpretation will be the most interesting from a learning point of view.

A different testimony is given by **R3**, who saw and participated in two hysterectomies before viewing the video-based training for the first time, and continues to participate in hysterectomies.

" Yeah, well, I find that the video, in fact, it's halfway between theory and practice. Because [the video contains] all the theory in fact, [...] you have to pay

attention to that, etc. But at the same time, you still have this almost practical part in the sense that you see, you see the key steps at the moment when they are described" (**R3**).

and:

"As time goes by, it becomes clearer. Because you know the theory and you can see in practice, what corresponds to what" (**R3**).

About the clarity of the video:

"Honestly, it seemed clear to me. I think there was the necessary information, there wasn't too much excess either" (**R3**).

R3, unlike **R4**, not only has a need to know about hysterectomy in his/her daily practice but has also seen hysterectomies before so s/he has a mental representation of the procedure before starting the training. The video was watched and understood, and even specific missing elements could be identified:

"In the video, the practical things like pushing your scalpel in such a way that it will work well with this clamp rather than that one, all that, it's not precise. I think it's a little bit precise, but not much more." (**R3**).

Here, **R3** identifies a problem of comprehension in the definition of the scheme, being that the "*practical*" side of some of them is not found in the video. These are probably missing elements in the model, and therefore in the video, that are part of situational inferences that we have chosen not to include in the video.

R5 has also seen two hysterectomies before:

" Well, perhaps because I had seen them in laparoscopy, I already had the time to know which ligament it was and which stage we were at, why we were doing this. Well, perhaps I didn't know where, I don't know, I had a slightly blurred vision of the places, of the elements, and now, as a result, of seeing them again several times [in the video] with a clear head. Well, I can visualize better such ligaments, where they are inserted, where they come in, and why do we take this off? And why do we go this way?" (**R5**).

We can observe with these different situations how important practice is in the comprehension of the video first because it enables the exposition to similar situations as those presented in the video and hence contributes to creating the conceptions in a complementary way to the video, and second because it may or may not create the need to learn. It thus seems that without the experience of a real situation, the actions, goals, anticipations, rules of action and operative invariant described in the video do not succeed in generating the creation of a scheme according to the definition of Vergnaud. Additionally, as mentioned by **R5**, the knowledge contained in the video also appears to give practice a meaning. This is part of what allows us to affirm the complementarity of video and the operating room, they each bring essential aspects of learning. This statement leads us to the second sub-theme.

3.2.4.2 The best learning scenario lies in the repeated succession of the pedagogical video and practice

From this necessity to have seen hysterectomies in the OR to be able to understand the video and draw knowledge from it, a second one follows: the necessity to go back and forth between the video and the OR. The viewing of the video and the discussion about it highlights some deficiencies in the teaching that takes place in the operating room. We have already pointed out that the hours spent in the operating room are too few, but have not discussed what these hours do and do not bring to medical interns in terms of surgical learning. **R1**, who has seen and participated in hysterectomies before the first interview, mentions it:

"And so, yes, that's why the video has a good effect to say in retrospect I did that. [...] when we are taught sometimes, things are explained to us, or they show it by holding our hand and we don't think enough and seeing the video [afterwards] it can [..] reinforce a little bit the learning" (**R1**).

Here **R1** says two things: both that in the OR, the explanations are scarce or only given by demonstration and that the video is efficient in providing information that are missing in the OR.

R2, who has only seen hysterectomy but not taken part in any describes how practicing and going back and forth between reality and video will help him/her learn:

"Ah yes I think that [...] the more I will progress and the more I will be interested in different things on this video. I find that it is made to be seen several times as we progress, because for the moment I was taking it a little bit in informative mode but after I have seen it several times it will be: 'why do we put the [clamps] like that?', 'how do we do it', I find that we have a different understanding of the video as we progress" (**R2**).

These testimonies enable to better identify the shortcomings that interns face in their surgical learning process and how the video can help solve them by being complementary to the OR. Indeed it appears that in the OR, the explanations given are not enough to fully understand the gestures. In other words the *rules of action*, the *operative invariant* are not systematically explained to the attending surgeons. This can be partly explained by the fact that the OR is dedicated to care before being dedicated to surgical education. Efficiency and speed constraints that guaranty patient's safety are often applied at the expense of teaching time. As a consequence, surgical students are not given detailed explanations on what is happening, they are not given time to perform in a way that allows them to learn while performing -this would imply the risk of making mistakes that could be harmful for the patient-, and neither are they given explanations on *why* the gestures are done in such or such way. This is when the video makes sense, literally, of the images seen in the operating room.

On top of the reasons given before, the operating room as a place of practical application also fails at providing a fully comprehensive learning experience because of the fact that experts have automated, by dint of experience, the reasons why the make the decision to perform the gesture in such or such a way. As a consequence, they sometimes are unable to make these reasons explicit.

This is explained by Vergnaud in an other situation: *"This discrepancy between the finesse of the action and what can be said about it does not only concern the workers and technicians. About thirty engineers who designed the Ariane launchers, and who had become great experts after 12 or 15 years of experience, were asked to write "methodological guides". These guides were intended for the training of young engineers, as well as for the establishment of the company's own competences for its negotiations with other companies, French or foreign. A reading of these guides shows that, however expert they may have been, these engineers did not convey certain decisive elements of their professionalism: for example, they gave an almost purely sequential vision of their activity (we do this, then that...), leaving out the reasons for their choice, and the conditional reasoning which accompanied them. Similarly, they did not mention the cost/effectiveness criteria, which are nevertheless crucial for the choice of the technical solutions chosen"* [166].

In the same way as in the story told here, in the OR, the residents do not have access to the reasons behind the gestures. The explanations are often brief and teaching is done by demonstration rather than by instruction. Yet, **R2** underlines that *"it is very important to explain during the intervention, otherwise we are completely blind. [...] It is very difficult to imagine what you see in picture [in laparoscopy] in real life, it's very important to know the anatomical references and everything"* (**R2**). For **R2**, not having the explanations behind the gestures equals to *being blind*. At the opposite, not going to the OR, for reasons previously explained, hinders learning of the knowledge explained in the video. It is these observations that lead us to affirm that the best learning scenario lies in the repeated succession the pedagogical video and practice.

Going to the OR, as mentioned by **R2**, changes the perception of the video, and helps to *realize better*:

"We realize better in real life [...] there is a big difference between reading slides and saying 'ok, we'll do it like this, we'll do it like that' and seeing it in real life." (**R2**)

And also helps to:

"anchor the knowledge learnt before and then to really integrate it so yes it is in the continuity in my opinion of the theoretical knowledge" (**R5**).

While the video appears to put a light on the knowledge that remains inaccessible -because untold- in the OR, the *anchoring* and *integration* of this knowledge takes place in the OR. Seeing the action performed or taking part in the performance in the OR, after viewing the video, gives action a meaning and a purpose that is not only purely conceptual and theoretical. These considerations must be put into the context of learning for medical residents: their presence is required in the "field" for many hours, to analyze and work on the resolution of numerous and varied situations, both inside the OR and outside the OR. A theoretical knowledge that is learnt can only be *integrated* if it is used in a real situation, with the genuine aim of solving a problematic situation. Performing or participating in the performance using this theoretical knowledge is one of the ways, if not the only way, to assimilate it.

This moment of meaning-making and assimilation is very well described by Huard (2010):

"Situational experience is an opportunity to carry out the process of pragmatic elaboration, the process by which a concept acquires meaning for a subject through the situations in which s/he is involved. The return on the experience lived in situation in a training device cannot be a simple return on the action of the learner, but it is first of all necessarily a return on his activity of comprehension, of interpretation of the situations, of the activity of the more experienced others, and it is also a return on the interaction, on what was said there, what was done there" [69].

Hence the need to go back and forth between the pedagogical video, and practice. Because of the "difficulty" on the one hand, experienced in the OR where explanations are lacking, and because the OR gives learning a purpose, and is a moment of comprehension and interpretation.

It is this difficulty, made almost invisible to the experts because they have learned to distinguish, to identify, to locate, to perform, that the videos enable to minimize. In the OR, not making these reasons explicit to the medical residents has a subtle but not insignificant consequence that the interviews enabled to reveal: it makes them feel as if they do not belong to the medical team.

3.2.4.3 Acquiring knowledge with the pedagogical video results in a greater feeling of belonging

The consequences of this lack of explanation of the reasons that guide the actions is the feeling of not belonging (to the medical team, to the action) by the residents. **R3** describes how it feels not to have this knowledge:

"I ask questions to the surgeon, but sometimes there are questions that you don't dare to ask, you say to yourself that it's a stupid question and you don't want people to think that you're useless, so sometimes you don't ask the question and then you don't really know" (**R3**).

Yet sometimes, the residents are invited by the experts to perform the gestures as a way to teach them to do it, but they are always fully guided when performing gestures in the OR, and have no explanations neither on its *how* nor on its *why* *i.e.* on the *rules of action* that apply, the *operative invariant*, the *controls* that have to be performed to verify the rules of action. **R6**, who has participated in several hysterectomies, speaks of it in these terms:

"It's true that, for example, if [the expert] holds her scissors in one direction rather than the other, she won't necessarily say I'm holding my scissors in this direction because [...] if she gives me the scissors in my hands and I don't do it right, she'll say no. You have to hold it in this direction [...]. But I wouldn't necessarily have known in advance because I hadn't been told before and afterwards, regarding the stages too, when she advances in the surgery, when she goes from such and such gesture to such and such gesture, she doesn't necessarily think that she needs to specify what she is doing, she won't necessarily do it" (**R6**).

The reasons for the impossibility of access to this knowledge are twofold: because the experts have automatized the gesture, as mentioned and before, and because the stress is too high for the residents to be in good conditions to learn. This results in the impossibility for the residents to rely only on the OR for their surgical education.

R7 has also participated in several hysterectomies, including two between the first and the second interview, which means at the time the videos were available to him/her and he/she watched them, and describes it this way:

"No, you couldn't learn everything in the OR because there is the time constraint in the OR, which means that even if the chiefs try to explain as much as possible, there are always things that they don't explain and that seem logical to them because they have done it 500,000 times and that in fact for you it is not logical. No, I think that not everything is .... It's not possible to learn everything in the OR" **(R7)**.

Indeed, **R7** also mentions how the stress hinders the ability to learn in the OR.

The problem is not only the few hours spent in the OR, but also what is taught during those hours and how it is taught. A part of the teaching necessary to the realization of the surgical gesture does not cease escaping to the resident. This knowledge will reach him/her only by dint of numerous and varied repetitions, which equals to great determination and hard work to succeed in retrieving it.

About the distribution of knowledge within the medical team, and his/her role as a "help" **R6** makes interesting comments:

"I think that it is the operator who needs to know, to know the steps since the help at the end, s/he is only following. You have to anticipate the operator's gestures. Clearly, when I was holding the forceps, I did exactly what the surgeons told me to do. So, I don't know if it would have changed anything for me to have reviewed or not. And so, I think actually, everybody, whether it's the assistant or the operator, we need to know what's going to happen, for the smooth running of the intervention" (**R6**).

The comments made are paradoxical but provide important elements in the understanding of how the concepts described in the video and derived from the model can change the course of the intervention. **R6** mentions that s/he was fully guided when performing a gesture during a hysterectomy and therefore she wouldn't have needed to know more about it to do it properly. Still, s/he also indicates that "for the smooth running of the intervention" every member of the medical team should be able to anticipate what is going to happen next *i.e.* to know the actions, goals and anticipations.

And **R1**, about a gesture s/he had previously done in hysterectomy, and that the video helped her/him understand:

"When I did it, I had a lot of support, I was accompanied in the gesture. When I did the gesture, I didn't think about it exactly, I didn't know exactly how to do it. I followed the movement of the hand that was necessary to perform, so yes, having seen the video, it makes me rethink how I had made the gesture and therefore, in what way it is necessary to hold the instrument, well how I had to do it" (**R1**).

In this case, viewing the video even after having performed gestures during a hysterectomy, helped **R1** understand *the reasons* behind the gesture that s/he had not been explained during the intervention.

R1 also specifies:

"It was just at the time of the colpotomy in the last video when we did it in laparoscopy, just, I had not understood how to turn the uterine manipulator and there it was much clearer how it was explained [in the video] well it's silly because you just have to turn it. But I hadn't seen the shape of the instrument and so it didn't really work. So it just reminded me of that." (**R1**).

R2 also speaks of the part played by the video in the learning process:

"I think it's the video that brings [the theory] because they don't necessarily tell us the name of the steps, like they say here you do like this you do like that but like that it's not very theoretical it's more technical stuff that they give us as advice and not really theoretical stuff and given that we don't have any course on that I think that the video has done this work" (**R2**).

And about how the absence of explanations on the *how* and the *why* of the gesture makes them feel, **R6** has very specific words:

"For example, even if [the expert] tells me [to perform] gestures it would be nice if she could tell me why do this and not that. Because such and such a reason. And then, if we did that it would do that, that [the expert] explains the reasons and not just make us the technician of the operation" (**R6**).

The result is a feeling of being left aside and used as a "technician". Without knowing the reasons underlying the gestures, the attending surgeons are unable to gain proficiency, and as a consequence, they feel left aside.

When experts do explain, in most cases, residents are too stressed, their attention is overloaded by the fact that they are eager to perform correctly as they are told to perform, and that they want to anticipate the needs, the gestures of the expert. The attention is "broke" into little elements and it is hard for the learners to take a step backwards and have a global understanding on the intervention: its steps, its risks etc. **R5** speaks about it in the following way:

"But when you're in the OR, you may be more stressed, you're there without being there and you concentrate a bit on things and you forget steps" (**R5**).

This sub-theme also feeds the idea that the pedagogical video and the OR and complementary. So does the last sub-theme, which is about the creation of a conception by linking gestures performed in the operating room in a certain context such as a cesarean section, and gestures seen on the video performed in a different context: the hysterectomy.

3.2.4.4 The operative invariant

Participants who did not practice the intervention showed in the video, the hysterectomy, during their current internship, interestingly still benefited from it by making connections with gestures performed everyday during other surgical interventions. This is what we have called the *operative invariant* and is a direct observation of the creation of a conception in the sense given to it in the conceptual fields theory. The concept is here given meaning through different kinds of situations, each of which partially deconstructs the concept as dependent on a single situation and integrate it in a conceptual field that includes various different situations for the same concept.

R4, who does not practice hysterectomy during her/his internship, still mentioned that viewing the video s/he was able to make a link with her daily practice, the C-Section. S/he mentions bladder detachment, performed during C-Sections, and while visualizing the video, discovered in the context of hysterectomy:

"Yes, where it was a bit useful and I found it interesting, was the bladder detachment part, since we do a bit of that in C-Section. And I found it funny

to have the approach a little more surgical because in C-section it's a little bit the bladder that bothers us, so we kind of just get rid of it but don't bother too much. But yes, it was a little more, more detailed [in the video]. [...] That was interesting" (**R4**).

Even though most of the video was not understood or of interest to **R4** who does not perform hysterectomies on a daily basis -and never performed any except an emergency one-, an *activity* presented in the video still caught her/his attention, because performed in another context. Here, the participant learned by being able to navigate between different surgical interventions during which identical conceptions are used, but in different contexts, requiring different *goals and anticipations*, and *rules of action*. This a typical situation of learning in Vergnaud's conceptual fields theory [165]. By deciding to focus only on open hysterectomy and its different variants (total, interannexal) we had not anticipated this situation.

R6 also mentions making similar connection but regarding the incision *activity*:

And another for the Pfannenstiel incision: *"Since I saw the video, I haven't done a hysterectomy. But I have done C-sections and as the video details the Pfannenstiel, I used it for C-sections. It helped me during the C-Section."* (**R6**).

Here, too, learning occurs in a way that is very beneficial to the learner: by drawing parallels with an already known conception, but by encountering it in a different context with different constraints that apply to it. The same kind of learning situations are encountered when participants are mostly used to seeing laparoscopic hysterectomies, while the video shows a laparotomy hysterectomy, **R6** talks about it this way:

"Also, I had never seen a open hysterectomy, but only a laparoscopic hysterectomy, and I think that overall, we find the same steps" (**R6**).

And **R5** says:

"I think that the structures remain the same [between laparoscopic and open hysterectomy] -it's not the same angle, it's not the same vision exactly, but in itself, it remains the same steps in more or less the same order but with the same structures. So, I think that yes, it will help me to better visualize the anatomical structures" (**R5**).

Here, the *actions, goals, anticipations, rules of action* and *operative invariant* strictly related with laparoscopic hysterectomy instead of hysterectomy by laparotomy (shown in the video) remain unknown -at least they are not given to the learners by the video. Still, between the two surgical interventions, or rather between the two ways of performing the surgical intervention (by laparoscopy or by laparotomy), there exists operative invariant: *"categories with which the subject takes from the environment the relevant information for his actions"* [164]. These categories form a knowledge which allows to *"generate, consciously or unconsciously,* *rules of actions, actions and anticipations"* related to every particular situations. Because some of the interviewed medical residents had participated in laparoscopic hystere-ctomies before, they had acquired part of the knowledge which constitutes the operative invariant related with hysterectomy, and viewing the video, they were then able to extend each of these categories with novel knowledge. Rather than a creation of categories, the video engendered an enrichment of categories: such as, as mentioned by **R5**, *"the steps"*, the *"[anatomical] structures"*. However, the same participant (**R5**) explains that the *"angles"*, the *"vision"* differ, these are the elements enriching the categories. This observations also contributes to emphasizing the complementarity of the pedagogy-based video and of the OR.

3.3 Discussion

The results obtained in our study suggests that major improvements can be made in surgical education, not by means of technological advancements, but by means of more pedagogical training. The study enables identification of the types of not so obvious difficulties faced by residents in medicine when trying to learn surgery and the impact of the use of human learning model to develop video-based surgical training on the reduction of these difficulties (as for example the fact that it allows for the creation of meaning before or after the realization of the gesture, the fact that it results in the creation of multi-situational conceptions, that it improves residents feeling of belonging to the medical team etc.)

The purpose of developing video-based training within a human learning theoretical framework is not to replace or to differentiate from the apprenticeship model which is still very important in surgical education, but rather to complement it with elements that it lacks today. Whereas the Halstedian saying recommends to "See one, Do one, Teach one" it is as if today administrative and time constraints prevented the experts from doing the last, teaching part. To see and to do according to the residents testimonies appears to be the only elements that are still used by experts to teach interns while a whole part of the knowledge essential to perform the gesture, remains inaccessible to them.

Applying a human learning model to recorded videos of interventions allows for a systematic segmentation of these videos and the design of a training scenario, by adding text annotations and/or audio comments. It gives students in surgery the opportunity to train on realistic situations. Although this process may seem time consuming, it has the potential to reduce the surgical learning curve which is currently based on experience in the OR and thus requires an important quantity and variety of interventions to reach all of the learning objectives.

Some points of the experiment yet deserve more detailed comments. First, some of the problems, operators and controls presented may not reach total agreement between experts. In our case, only two experts were consulted to design the model. A broader cohort of surgeons, as well as the measurement of their agreement on each element of the model, would reflect a more accurate modeling of laparoscopic hysterectomy. Second, the model presented here details a benign case of hysterectomy. It could be extended to more specific pathological cases to which students are not necessarily fortunate enough to have access, or simply to laparoscopic hysterectomy. Third, our study is very exploratory in nature.

The interviews revealed an interesting point on which we encourage the development of future, less exploratory research: the process of creation of the surgery-related conceptions. During the interviews, links were made by attending surgeons between the pedagogy-based videos and the reduction of difficulties faced when trying to train for surgery. Still, because the interviews were not focused on a particular topic, they do not allow for demonstration of a concrete situation of learning of a surgery-related conception: the moment of understanding, for one surgical gesture, of all the goals and anticipations that may condition its realization, all the rules of action, the operative invariant that condition the way in which it is realized, in each different intervention domain it applies. A whole study could be conducted on this specific topic, and would give precious information on the existing links between pedagogy and surgical education.

3.4 Conclusions

Although numerous solutions are developed for students to have access to surgical training outside of the OR, from bench-top models to simulation to manikins, VR, AR, videos etc., surgical training still seems difficult to access for medical school students. They easily mention that they have *nothing to train with*, because of the *lack of time*, because solutions are too *expensive*, *not pedagogical enough*. This discrepancy can be partly explained by the fact that high-technological learning material for surgery are often developed rather as a technological achievement than to significantly increase surgical student's knowledge and skills in surgery. This is demonstrated by the number of simulators focused on training the technical skills of interns rather than their knowledge of anatomy, risks, steps of procedure, instruments, decisions to make in case of advert event etc. Yet, this know-how is the majority of the surgical expertise. As mentioned several times by the medical residents, it is not -or rarely- either explained inside the OR.

This first experiment enabled to show that a pedagogical video had a positive impact on this matter: the inaccessible knowledge became accessible. As a consequence of viewing the video, gestures seen in the OR that were not understood, in retrospect had a meaning, a purpose, the back and forth between the OR and the video made the meaning given to each of them evolv and finally, the knowledge acquired through viewing the video and viewing hysterectomies in the OR reinforces the feeling of belonging the medical residents.

Yet, considerations in the creation of the learning script were only pedagogical and not technological. Technological considerations may certainly strengthen the impact of the video on the medical residents difficulties by making them more attractive, more accessible, more pleasant to watch, more interactive and therefore adaptable. But pedagogical ones seem more fundamental as they have the ability to reintegrate the learner in the surgical practice by making him/her go from being a passive "service provider" to being an active, understanding, decision-maker part of the medical team -which does not imply that the decisions have to be taken effectively putting the patient at risk, but can be proposed and formulated, and above all understood.

3.5 Contributions of the chapter

This chapter presents the methods and theories behind the creation of a pedagogical video-based surgical training. The concepts, approaches and measuring instruments used for this purpose are described. An exploratory study is presented, which aims at highlighting not only the difficulties faced by residents in medicine when training for surgery but also the practical and specific consequences of these difficulties, and how they can be alleviated by a *scripting* of learning. What is meant by *scripting* of learning is the theoretical framework that guided the creation of the video and which enables to elicit and to methodize the exposure of the knowledge that is essential to the realization of the gesture. The interviews conducted with residents in medicine trained with a scripted video-based training on hysterectomy and who perform gestures in hysterectomy, enable to determine that the difficulties are not only due to the lack of time spent in the OR or the ever increasing administrative burden as was mentioned before.

The difficulties are also found in the lack of explanations given in the OR, or even in the existing learning materials that are either not realistic enough or not didactic enough. Additionally, the comments made during the interviews show that the scripting of learning on the basis of a human learning model has the ability to ease these difficulties by giving meaning to the gestures seen in the OR as a result of which residents in medicine feel more a part of the medical team, and are able to *learn* in the sense given to this word by Vergnaud, *i.e.* are able to navigate between conceptions: to have a mental representation of a similar action in different contexts, knowing the different goals and anticipations, rules of action and operative invariant which apply in each context.

The study carried out here enables to determine that technological developments are not the only ones capable of improving the training of interns, and it may well be that they are the least capable of doing so. Technological developments are more valuable for the experts while advances in terms of pedagogical support for the development of surgical training seem to have a very high capacity to improve surgical training.

Chapter 4

Towards techno-pedagogical systems

In this chapter, after detailing a state of the art on techno-pedagogy and the main theories that represent it, we present an experimental protocol which aims to investigate the impact of including such theories in video-based surgical learning on medical school residents' knowledge, skills, and experience as learners. As mentioned before, some work have focused on *Intelligent Tutoring* for surgical education [95; 93; 163; 158] but none, to our knowledge, in the context of gynecology, a medical specialization which requires, among other things, an excellent ability for tissue identification, fine anatomical knowledge, meaning a capacity for complex decision making.

4.1 State of the art

4.1.1 The definition of techno-pedagogy

Techno-pedagogy refers to, as defined by the Interdisciplinary Research Group in Langages & Technology at the University of Ottawa, " *(teaching) practices that take into account both pedagogical (teaching and learning methods, motivation, the development of students' skills), and technological aspects (using computers, the Internet, interactive whiteboards, etc.). [...] Technology, therefore, is considered as a mean to support active teaching methods, and not as an end in itself. The common goal of those innovations is to improve the quality of the students' learning.*" [tec]. Hence creating techno-pedagogical systems means considering both pedagogical and technological components and constraints, as well as the association of these elements, which create new components and constraints. There are existing models of learning which are based on techno-pedagogy and we describe one of these.

4.1.2 The Technological Pedagogical Content Knowledge (TPACK)

Matthew J. Koehler and Punya Mishra are two researchers with expertise in psychology, education and technology who created a framework, called technological pedagogical content knowledge (TPACK) based on Lee Shulman's construct of pedagogical content knowledge (PCK) [146] -described later on. They state that:

> *"Teaching is an example of an ill-structured discipline, requiring teachers to apply complex knowledge structures across different cases and contexts [106; 149]. Teachers practice their craft in highly complex, dynamic classroom contexts [88] that require them constantly to shift and evolve their understanding. Thus, effective teaching depends on flexible access to rich, well-organized and integrated knowledge from different domains [52; 131; 146; 145], including knowledge of student thinking and learning, knowledge of subject matter, and increasingly, knowledge of technology. [...] particular technologies have their own propensities, potentials, affordances, and constraints that make them more suitable for certain tasks than others. "* [79].

Punya Mishra and Matthew J. Koehler's 2006 TPACK framework [105], which focuses on technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), offers a productive approach to many of the dilemmas that teachers face in implementing educational technology (edtech) in their classrooms. By differentiating among these three types of knowledge, the TPACK framework outlines how content (what is being taught) and pedagogy (how the teacher imparts that content) must form the foundation for any effective edtech integration. This order is important because the technology being implemented must communicate the content and support the pedagogy in order to enhance students' learning experience. According to the TPACK framework, specific technological tools (hardware, software, applications, associated information literacy practices, etc.) are best used to instruct and guide students toward a better, more robust understanding of the subject matter. The three types of knowledge – TK, PK, and CK – are thus combined and recombined in various ways within the TPACK framework.

Technological pedagogical knowledge (TPK) describes relationships and interactions between technological tools and specific pedagogical practices, while pedagogical content knowledge (PCK) describes the same between pedagogical practices and specific learning objectives; finally, technological content knowledge (TCK) describes relationships and intersections among technologies and learning objectives. These triangulated areas then constitute TPACK, which considers the relationships among all three areas and acknowledges that educators are acting within this complex space.

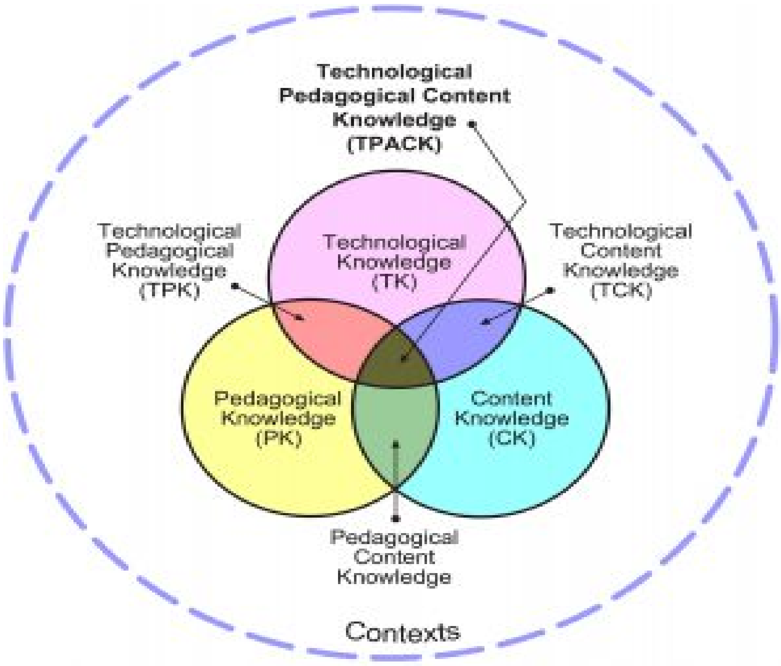


FIGURE 4.1: TPACK

Content Knowledge (CK) – This describes teachers' own knowledge of the subject matter. CK may include knowledge of concepts, theories, evidence, and organizational frameworks within a particular subject matter; it may also include the field's best practices and established approaches to communicating this information to students. CK will also differ according to discipline and grade level – for example, middle-school science and history classes require less detail and scope than undergraduate or graduate courses, so their various instructors' CK may differ, or the CK that each class imparts to its students will differ.

Pedagogical Knowledge (PK) – This describes teachers' knowledge of the practices, processes, and methods regarding teaching and learning. As a generic form of knowledge, PK encompasses the purposes, values, and aims of education, and may apply to more specific areas including the understanding of teaching strategies, classroom management skills, lesson planning, and assessments.

Technological Knowledge (TK) – This describes teachers' knowledge of, and ability to use, various technologies, technological tools, and associated resources. TK concerns understanding edtech, considering its possibilities for a specific subject area or classroom, learning to recognize when it will assist or impede learning, and continually learning and adapting to new technology offerings.

And their different combinations:

Pedagogical Content Knowledge (PCK) – This describes teachers' knowledge regarding foundational areas of teaching and learning, including curricula development, student assessment, and reporting results. PCK focuses on promoting learning and on tracing the links among pedagogy and its supportive practices (curriculum, assessment, etc.), and much like CK, will also differ according to grade level and subject matter. In all cases, though, PCK seeks to improve teaching practices by creating stronger connections between the content and the pedagogy used to communicate it.

Technological Pedagogical Knowledge (TPK) – This describes teachers' understanding of how particular technologies can change both the teaching and learning experiences by introducing new pedagogical affordances and constraints. Another aspect of TPK concerns understanding how such tools can be deployed alongside pedagogy in ways that are appropriate to the discipline and the development of the lesson at hand.

TPACK is the end result of these various combinations and interests, drawing from them – and from the three larger underlying areas of content, pedagogy, and technology – in order to create an effective basis for teaching using educational technology. In order for teachers to make effective use of the TPACK framework, they should be open to certain key ideas, including:

concepts from the content being taught can be represented using technology, pedagogical techniques can communicate content in different ways using technology, different content concepts require different skill levels from students, and edtech can help address some of these requirements, students come into the classroom with different backgrounds – including prior educational experience and exposure to technology – and lessons utilizing edtech should account for this possibility, educational technology can be used in tandem with students' existing knowledge, helping them either strengthen prior epistemologies or develop new ones.

It is on the basis of these assertions that we wish to direct research in surgical education towards the consideration of a greater number of the mentioned factors. One way of doing it is using human learning theories and models in the creation of a video-based training for a surgical intervention, as well as different visualization devices in an experimental protocol to test for each of their "*propensities, potentials, affordances and constraints*" from a learner's point of view.

4.1.3 The Pedagogical Content Knowledge (PCK)

Previously mentioned, the Pedagogical Content Knowledge (PCK) is a concept which was developed by Lee Shulman in the mid-1980s [146]. The concept is based on the idea that, on top of the subject knowledge and general pedagogical skills, teachers must know how to teach topics in ways that learners can understand. Shulman says teachers' expertise lies *"in the capacity of the teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful and yet adaptive to the variations in ability and backgrounds presented by the students"* [145].

According to Shulman (1986) pedagogical content knowledge:

"embodies the aspects of content most germane to its teachability. Within the category of pedagogical content knowledge I include, for the most regularly taught topics in one's subject area, the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others. Since there are no single most powerful forms of representation, the teacher must have at hand a veritable armamentarium of alternative forms of representation, some of which derive from research whereas others originate in the wisdom of practice." [146].

On top of that,

"Pedagogical content knowledge also includes an understanding of what makes the learning of specific topics easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons. If those preconceptions are misconceptions, which they so often are, teachers need knowledge of the strategies most likely to be fruitful in reorganizing the understanding of learners, because those learners are unlikely to appear before them as blank slates. Here, research on teaching and on learning coincide most closely." [146].

The PCK incites to think, when creating a scripting of learning, not only to the subject taught, but also to the way of representing the elements of the subject taught, the *analogies, illustrations, examples, explanations and demonstrations* while paying special attention to the learners' previous knowledge, *conceptions and preconceptions.*

This model is at the origin of the TPACK. In the experiment we conducted (described below) which presents a techno-pedagogical training for the realization of the caesarean section, we carry out a reflexive work, in the scripting of the training on the different elements that contribute to its creation: the Pedagogical Knowledge (PK), the Technological Knowledge (TK), the Content Knowledge (CK).

4.2 Our approach: the case of C-Section

FIGURE 4.2: Participant visualizing the video with the high-technology media *i.e.* the Virtual Relality Helmet

In the experimental protocol presented here, we propose a video-based training for the Caesarian Section (C-Section), that roots in a pedagogical theoretical framework, and follows techno-pedagogical guidelines (for content, technology, and demonstration selection). We study the impact of this video-based training depending on its content (either based on pedagogical theories or strictly demonstrational), and the media used (high-technology or low-technology) on knowledge skills and experience of medical school students.

4.2.1 The TPACK applied to surgery

4.2.1.1 Definition of terms

We aim to pursue the techno-pedagogical practices and goals in this study. Hence here, the **Pedagogical Knowledge (PK)** refers to the understanding of the teaching practices in surgery, including the apprenticeship model and its famous

Halstedian “See one, Do one, Teach one” [82]. This model, even with the expansion of the repertoire of tools available to the surgeon, still plays an important part in surgical education, as the attainment of safe and efficient surgical technique still depends on the same comprehensive knowledge of basic surgical skills. Yet, a number of changes in the practice of surgery put the apprenticeship model under strain. The PK also refers to the recognition of these changes in surgical practice environment and their consequences: the resident work-hour restrictions (resulting in less opportunities to observe surgical practice) [30], the realities and legalities of the business of medicine (changes in reimbursement and other insurance and medico-legal issues which threaten to serve as a rigid surrogates for quality) [16] and the shift in practice pattern [39] (the outpatient surgery centers draw cases away from hospitals and this shift negatively impacts resident training volume). The PK on surgical education strengthens the evidence of the need for easily accessible, knowledge-based, instructive, and interactive training for surgery.

The **Technological Knowledge (TK)** refers to the recent work which have shown the interest of Head Mounted Displays (HMDs) for learning, especially in Virtual Reality (VR) [124; 84; 60; 132], as it creates a feeling of immersion that enables better focus, a sense of realism that engages the learner in the exercise, enables to display interactive and level-adaptive 3D videos developing extended knowledge on the procedure and visuo-spatial ability which is a major component of surgical education. The use of HMDs, or VR helmets reduces learning time, augments learning frequencies and liberates temporal and material resources for other activities [124]. Finally, they also increase the degree of involvement for the task compared with videos viewed on a standard screen, and enable to give immediate feedback on performance [159]. They draw enthusiasm among students [71; 70]. The TK also refers to the fact that video-based training, whether viewed on a standard screen or in an HMD, is recognized for allowing for repeated and stress free training. It is of major interest knowing that the difficult access to the OR, the too little observation time and the stress that the presence in the OR implies for students are among the factors that hinder training the most [128]. Based on these assumptions, in the experiment presented here, both the knowledge-based video training, which is founded on pedagogical theories, and the demonstrational video for the C-Section are visualized by the medical school participants either on a low-technology standard computer screen that displays the video in 2 dimensions, or in a rather high-technology media, an HMD that displays the video in 3 dimensions.

At last, the **Content Knowledge (CK)** refers to the knowledge on the chosen surgical intervention, the C-Section, captured through hours of observation in the Operating Room (OR), interviews with experts and surgical students, and literature reading. The C-Section was selected because it is one of the first to be performed, in France, sometimes entirely by residents in medicine specialized in gynecology-obstetrics at the beginning of their residency. Hence training 1st year residents on the C-Section enables to have the opportunity to directly measure and observe the consequences on their performance in the OR. The CK in this case also refers to the application of a constructivist learning theory [47]: the conceptual fields' theory [165].

A conceptual field, as initially defined in the previous chapter is both a set of classes of situations, and as a set of interconnected concepts. This theory presents the relations between explicit knowledge and the implicit operational invariants that underlie schemes [165], which are, according to Piaget, the invariant organization of behavior for a certain category of situations [168]. In Vergnaud's own words, the conceptual fields theory *is based upon the fact that students' competences and conceptions develop through experience and that there are high regularities in the difficulties students have to overcome. [...] It is a matter of fact that a concept cannot be made meaningful through one kind of situation alone; similarly a situation cannot often be analysed with just one concept. This implies that the formation of several interconnected concepts needs to be studied concomitantly* [165]. The learner has to be able to represent given situations in a conceptual field, and either activate a relevant scheme to deal with it, or *map this situation into a symbolic representation and then operate inside this representation until the solution is reached.* In the previous chapter, this theory was used to guide the scripting of a learning scenario for hysterectomy.

Adapted from this theory is a model of human learning, ckc [15], that adds to the conceptual fields the control structures *i.e.* the elements which insure conception consistency and the tools needed for decision making. In this model, a conception is neither dependant to a learner nor to an environment, but is rather a property of an interaction between the learner and the environment. The challenge of this interaction is to meet the viability conditions of the system, the stable conditions of equilibrium and the ability to regain them after a disruption *i.e.* problem. We use this model to develop the knowledge-based video, called the More Informative Video (MIV) while the Less Informative (LIV) and rather demonstrational video is also developed, that does not root in human models and theories. The details of how the human model is used as a base to create the MIV is detailed later on in the article. The relationships and intersections between the three types of knowledge, are explored through the experiment presented here in two ways: the pedagogical content knowledge (PCK) and the technological content knowledge (TCK).

4.2.1.2 The cKç model

In the conceptual fields theory, G. Vergnaud [165] characterized a student's conceptions with three components: *problems, systems of representation* and *operative invariants*. N. Balacheff then explicitely added the control structures to this theory, to make the cKç model [14]. In this model, a conception is neither dependant to a learner nor to an environment, but is rather a property of an interaction between the learner and the environment. The challenge of this interaction is to meet the viability conditions of the system *i.e.* the stable conditions of equilibrium and the ability to regain them after a disruption *i.e.* problem.

A conception is then characterized by a quadruplet (P,R,L, $\sum$) in which the four elements respectively represent:

- P, a set of problems. Pragmatically speaking, this is the *practice area* of the conception.
- R, a set of *operators*, action that have consequences on the state of the world
- L, a representation system
- $\sum$ a control structure. $\sum$ describes the elements that insure conception consistency and includes the tools needed for decision making.

The representation system L, enables formulation and manipulation of operators by the learner, and environmental feedback. The control structure $\sum$ enables expression and discussion of the learner's means to decide for validity and adequation of his/her action.

During this experiment, one of the research questions focuses on how the application of this model to the creation of a C-Section training impacts the medical residents knowledge and skills.

4.2.2 Research questions

The primary research question is whether the video structure and its theoretical basis with regard to pedagogy, has an impact on knowledge acquisition of residents in medicine on the C-Section. It is about investigating how the Pedagogical Content Knowledge (PCK), which is the understanding of teaching, teaching practices and learning, may influence how effectively a learning video teaches surgical students knowledge they need in their daily practice. We investigate whether a C-section learning video that is produced and edited in a pedagogical theoretical framework, based on theories and models of human learning has a greater positive impact on knowledge of young residents, compared with a C-section learning video that has no such framework and basis, that is rather demonstrational.

We also, as an exploratory result, study whether the videos theoretical framework impacts residents skills in the OR. This result is only exploratory as homogeneous and numerous data in the OR is very difficult to obtain, because of the diverse cases encountered, the high pace to be maintained, and the fact that OR is a place that

Groups	Pre Clinical Knowledge & Videos in 2D & UEQ (**Step 1**)	Post Clinical Knowledge & Videos in 3D & UEQ (**Step 2**)	C-Sections & OSATS Score (**Step 3**)
MIV	16	16	6
LIV	12	12	9

TABLE 4.1: Number of participants at each step of the procedure (UEQ: User Experience Questionnaire, OSATS Score: Objective Structured Assessment of Technical Skill)

is dedicated to care before being dedicated to training. To investigate this primary question of research, participants were randomly separated into two groups: MIV group who viewed the knowledge-based videos and LIV group who viewed the non knowledge-based videos to train for the C-Section before performing it either on their own, or with an expert.

The secondary research question, is whether the device used to view the videos has an impact on the participants' satisfaction and experience, depending on the videos' content. It is about the Technological Content Knowlegde (TCK) which is at the crossroads between technologies and learning objectives: we investigate the influence of the training video's content on the appreciation by the surgical students of the technology to mediate it. To answer this question of research, the videos, either MIV or LIV depending on the group, were first shown to participants on a standard PC screen and second in a VR helmet to test for their experience using each of these devices to view the videos.

4.2.3 Methods and Material

4.2.3.1 Participants

Authors performed a multi-center study in France, including 32 residents in first year of residency, in gynecology-obstetrics specialization. These 32 participants were randomly assigned either to group MIV (n=16) or to group LIV (n=16). Of the 16 participants assigned to group MIV, 16 were able to participate in Step 1 and Step 2, among which 6 were able to also participate in Step 3 (cf table 4.1). Of the 16 participants assigned to group LIV, only 12 were able to participate in Step 1 and 2, and among them 9 were able to participate in Step 3 (cf table 4.1).

4.2.3.2 Material

Videos Shooting The videos are obtained from films recorded in operating rooms with a 3D camera Z-Cam K1 and a numerical camera Panasonic Lumix LX100.

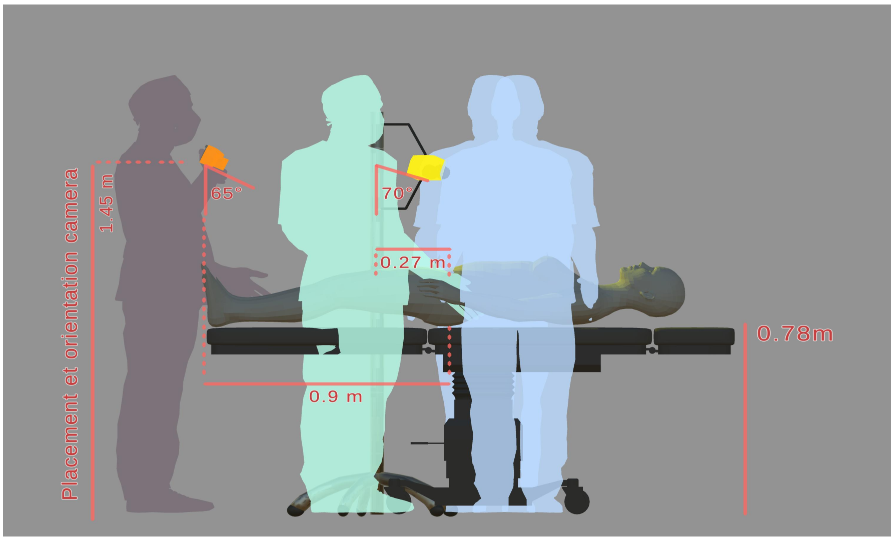


FIGURE 4.3: Video Shooting in the OR using a Numerical Camera -in orange for zoom view of the surgical gestures and a stereo camera -in yellow for filming 3D images of the sterile field.

The patients' consent for video shooting and sound recording was obtained prior to the surgical intervention. The surgical experts performing the intervention were aware of the purpose of the video and therefore did their best to be demonstrational when performing surgical gestures. The entire intervention was filmed from different points of view, in order to get a clear view of the whole medical team, but also a zoomed view of the surgical gestures. The use of the human learning model for the selection of important elements to put in the learning video is done after the video shooting, at the time of editing.

Videos content The videos are used as training for the C-Section. They show the entire OR during installation, the instruments' table and the operating field. In this study, two videos for training on a surgical procedure are used: one More Informative Video (MIV) that is filmed, edited and produced following a pedagogical theoretical framework and one Less Informative Video (LIV) that follows no such scientific principles when being edited and produced, and is rather demonstrational. The MIV is edited and augmented with learning material (audio and text) according to the theories and models of human learning cited earlier [47; 165; 15]. Both LIV and MIV contained a view of the OR that was either 2D (when viewed on the standard screen) or 3D (when viewed with the VR helmet), a zoomed view of the gestures being performed and audio comments on the gestures being performed but only in the MIV the implicit knowledge behind the gestures was made explicit.

More Informative Videos

In accordance with the elements found in the cKç model [15] cited in the Introduction, in the MIV, the learner is considered to acquire concepts by confronting

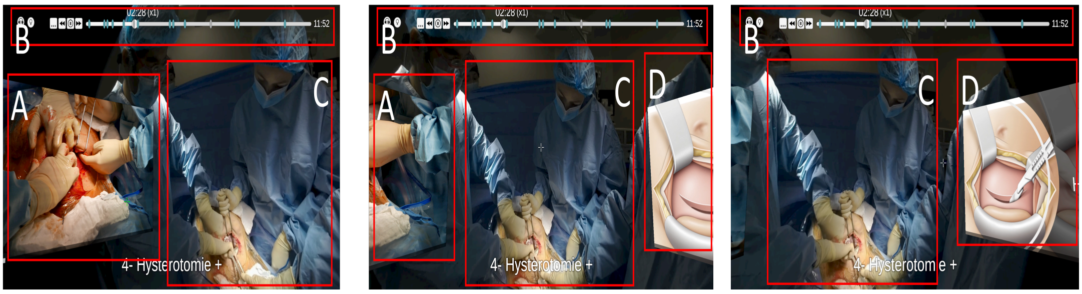


FIGURE 4.4: Left: The view from the left of the MIV (**A**: Zoomed view of the surgical gestures, **B**: Navigation toolbar, sound and light control, **C**: View of the sterile field), Center: The view from the center of the MIV (**D**: Anatomy boards and classes). Right: The view from the right of the MIV. In the VR headset, **C**: the view of the sterile field is visualized in 3 dimensions. On a standard screen, participants use their computer mouse to navigate in the video and focus either on the central film of the sterile field, the left film which show zoomed surgical gestures or the right view which displays anatomy boards and classes.

with "problems" or "steps" of the intervention, that are solved performing "operators" (actions that change the state of the world) and "controls" (actions that serve to evaluate before and after the operators) subtended by rules of action. The experts acquire these rules of action through years of experience. An example is presented in Table 4.2 for the "problem" or "step" of the hysterotomy that requires knowledge of rules of action and operative invariant, and to perform certain operators and controls to be executed without mistakes. They are not always easy to identify, as they are sometimes performed in automatically by the expert surgeon. They have become implicit to the expert. It is thus necessary to elicit them and deconstruct them so that they can be taught to others [77].

To retrieve the *rules of action*, and the gestures performed to confirm or infirm them called the *control actions* and return them in the videos, authors have been reading literature on the C-section, observing C-Sections and interviewing experts, in the same way it was done before for vascular surgery where the purpose was to build a video simulator for laparoscopic aortic surgery [99]. The procedure was found to include 8 steps identified as the problems, 44 operators to solve these problems, and 25 control actions underpinned by rules of action. These elements can be found in Appendix D. All were made explicit in the video using audio comments, anatomy boards, and schemes. This explicitation aims at providing the surgical students with the elements that will enable the creation of conceptions that are neither dependant on a learner nor on a situation, *i.e.* the representation of given situations in a conceptual field.

In the MIV, to display these information, participants see, in a 180° video: a 2D zoomed view of the surgical gestures (cf figure 4.4, **A**); auditory comments on the step performed (cf figure 4.4, **B**); a view of the operating room with a close-up on the patient's belly *i.e.* sterile field (cf figure 4.4, **C**); the soundtrack corresponding to this view; classes, information on the step performed (gestures description, every actor's actions, anatomy, instruments used, risks involved) and different anatomy boards each corresponding to the steps performed (fig 4.4, **D**). Participants are free to access or not the different elements of the video and to repeat them as many times as they want.

Step	Rule of action	Operator	Control	Operative Invariant
Hystero-tomy	If no difficulties are foreseen at the fetal extraction	Incise the uterus horizontally in a single block on the lower segment	Make sure you are at least 2cm above the bladder margin. Be careful not to injure any underlying fetal part	A transverse hysterotomy is less associated with a risk of subsequent uterine rupture
Hystero-tomy		Make a small central uterine opening with a scalpel		
Hystero-tomy	If difficulty is expected at fetal extraction such as placenta accreta	Incise the uterus vertically, on the uterine body (corporal hysterotomy)	Check for anticipated difficulty with fetal extraction	This type of caesarean section imposes the use of iterative caesarean sections, because this type of scar is more fragile and risks uterine rupture in the event of subsequent delivery by the natural route

TABLE 4.2: Problem *"hysterotomy"* and part of the related *"rules of action"*, *"operators"*, *"controls"* and *"operative invariant"*

Less Informative Video The LIV displays a clear view of the gestures performed,

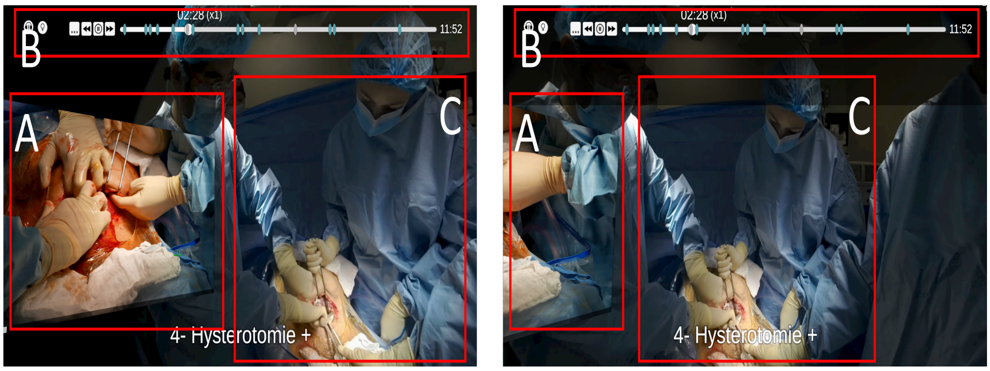


FIGURE 4.5: Left: The view from the left of the LIV (**A**: Zoomed view of the surgical gestures, **B**: Navigation toolbar, sound and light control, **C**: View of the sterile field. Right: view from the center of the LIV. In the VR headset, **C**: the view of the sterile field is visualized in 3 dimensions. On a standard screen, participants use their computer mouse to navigate in the video and focus either on the central film of the sterile field or the left film which show zoomed surgical gestures.

and a succinct audio description of the gestures performed. The rules of action are not clarified, neither are the control actions. Same as for the MIV, the participant has access to: a 3D view of an operating room with a close-up on the patient's belly; the soundtrack corresponding to this view; a 2D view even closer to the patient's belly; but has only limited auditory comments on the step performed; and no information on rules of action or control action that underlie the gesture (fig 4.5). Participants are also free to access or not the different elements of the video and to repeat them as many times as they want. In the LIV, participants see, in a 180° video: a 2D view zoom on the surgical gestures (cf figure 4.5, **A**); succint auditory comments on the step performed (cf figure 4.5, **B**); a view of the operating room with a close-up on the patient's belly *i.e.* sterile field (cf figure 4.5, **C**); the soundtrack corresponding to this view.

Visualization devices

Standard Screen The standard screen displays the videos in 2 dimensions. The 3-dimensional shapes, for the view of the sterile field (figure 4.5, **C**) are not seen. All other pedagogical content is perceived in 2 dimensions. In the MIV, the videos on the right side of the screen (figure 4.4, **B**) displaying "Class, anatomy boards step by step" are in 2D. In the MIV and LIV, the videos on the left side of the screen (figure 4.4, **A** and 4.5, **A**) displaying "Views of the surgical gesture step by step" are in 2D as well. The participants use their mouse to navigate in the video from left to right, up and down, and play/pause the different elements all three videos: the view of the sterile field, the right side video and the left side video (figure 4.4) for MIV group, and the two videos for LIV group: the view of the sterile field and the left side video (figure 4.5).

Virtual Reality Helmet The VR Helmet displays the view of the sterile field in 3 dimensions (figure 4.4, **C** and 4.5, **C**) with a close-up on the patient's belly, other videos are in 2 dimensions: one on the right side and one on the left side for MIV group (figure 4.4), and on the left side only for LIV group (figure 4.5). Participants are in total immersion.

4.2.3.3 Measuring tools and metrics

Related to the primary objective

- MQC: Before their first training session and after each training session, participants of groups A and B are required to fill up an MQC to test for improvement of their clinical knowledge on the C-section.

- Evaluation grid of gesture's quality (OSATS Score): When participants are performing C-sections during the first month of their first internship as a resident, two blind experts give them a score that reflects their technical abilities (respect for tissues, instruments handling, knowledge of procedure etc.). The OSATS score can be found in Appendix E.6

Related to the secondary objectives

- The UEQ is used to measure participants' satisfaction and experience after viewing the videos on a standard screen, both for group MIV and LIV, and after viewing the videos in 3D in a VR helmet, both for group MIV and LIV for the training they have received is filled by participants right after they have been trained

The results for every measuring tool are compared between groups of participants.

4.2.3.4 Procedures

There are two training sessions. Each training session includes one hour of interactive video viewing (S1,S2), each MIV or LIV depending on the MIV group or LIV group. There is a two weeks delay between the first two sessions. After the two training sessions, participants perform their first C-Sections as residents and are given a grade by experts during one month, these are the OR Evaluations (S3).

First Training Session (S1): The first training session took place in our laboratory, in a quiet environment. Either before their arrival or at the moment of their arrival, participants had to fill an MCQ (found in Appendix E) on their knowledge on the C-Section. Then, they were invited to watch either the 2D MIV for MIV group or the 2D LIV for LIV group. After having watched the videos, participants of each group were invited to fill a UEQ.

Second Training Session (S2): The second training session also took place in our laboratory so that participants all viewed the videos in the same, quiet environment. For every participant, it took place between one-two week after the first session. Upon their arrival, they were present with the VR HMD asked to take as much time as needed to position it correctly on their heads. They were shown the joysticks and explained how they worked. Once participants had understood how to interact with the videos, they started watching it, either the 3D MIV for MIV group or the 3D LIV for LIV group. They were told they could stop at any moment if they felt sick, or had a headache. Once they were done watching the videos, the participants were asked to fill the UEQ, and to answer again to the MCQ on the C-Section.

Operating Room Evaluations (S3) One week after their second training session, participants started their internship as 1st year residents in gynecology-obstetrics. They were asked, during the whole first month of their internship, to have their C-Sections evaluated by their chiefs using the OSATS score.

4.2.4 Results

This section presents 1. the impact of a theoretical framework, the Pedagogical Content Knowledge (PCK) and the associated human learning model, the ckç, for the creation of a training video on the C-Section on residents' knowledge and skills and 2. the impact of the device used to visualize these videos, referring to the Technological Content Knowledge (TCK), on residents' satisfaction and experience, depending on the videos content. Statistics are performed on results obtained at the MCQ as these compare between sufficient sets of data, but results obtained during S3 on technical skills are not statistically tested as the number of participants and hence the set of data are too small. Also, data obtained during S3 originate from the OR, representing different surgical interventions, performed in different hospitals: it very heterogeneous. These data are presented as tendencies and insights for future research rather than to corroborate the hypothesis.

4.2.4.1 Primary Research Question

Clinical knowledge

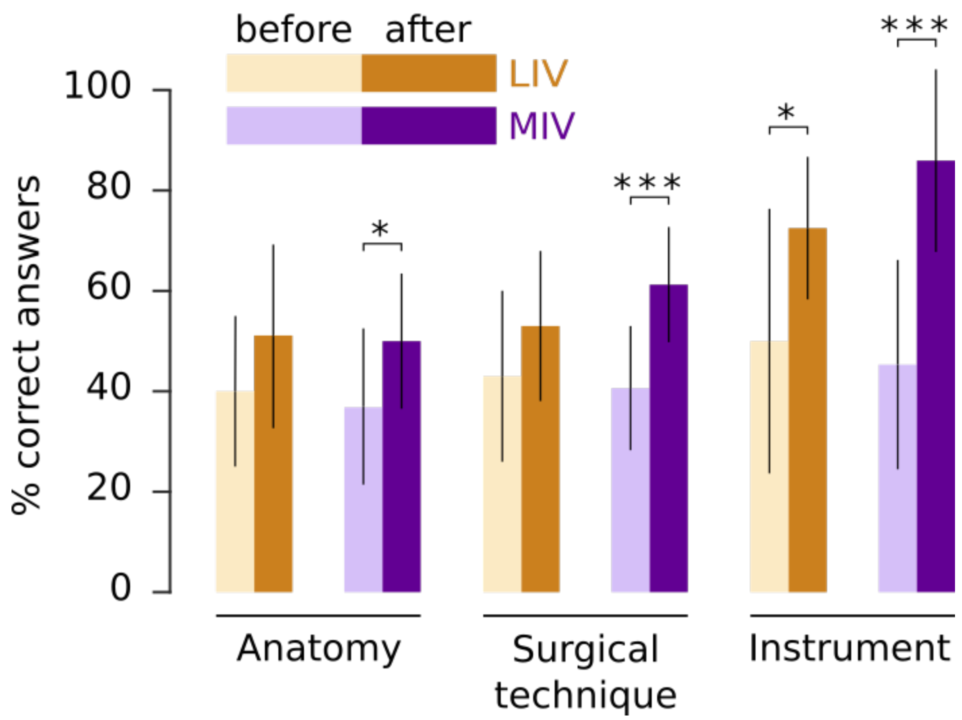


FIGURE 4.6: Before and After percentage of correct answers to MCQ Score for each participant in group Less Informative Videos (LIV)

Participants in the LIV group augmented their percentage of correct answers on anatomy in a non-significant way (paired *t test*, t(9) = -1.9365, p = 0.08), while participants in the MIV augmented it in a significant way (paired *t test*, t(15) = -2.4934, p =0.02). On surgical technique, participants in LIV group augmented their percentage of correct answers in a non-significant way (paired *t test*, t(9) = -2.2361, p = 0.05), participants in MIV group augmented it in a very significant way (paired *t test*, t(15) = -5.7446, p = 3.87e-05). On instruments, participants in LIV group augmented their percentage of correct answer in a significant way (paired *t test*, t(9) = -2.8620, p = 0.0187) and participants in group MIV augmented it in a very significant way (paired *t test*, t(15) = -6.3434, p = 1.31e-05).

Technical skills

Fifteen participants were able to send evaluation of their first C-Section as a resident in gynecology-obstetrics. Among these 15 participants, 9 were trained with MIV and 6 with LIV.

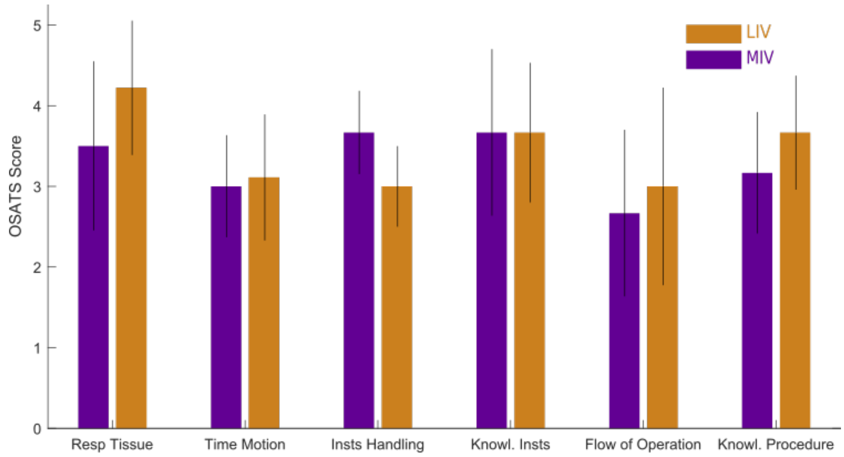


FIGURE 4.7: Mean OSATS Score during first C-Section for participants in group Less Informative Videos (LIV), n=6 and More Informative Videos (MIV), n=9

The two groups performed equivalently on average on all variables of the OSATS Score, with a mean of 3.2 (± 0.4) for LIV group and 3.4 (± 0.5) for MIV group. Still differences are observed in performance between the two groups for ability to respect tissues and handle instruments. At Respect for Tissue, MIV group performs better than LIV group with a score of 3.5 (± 1) compared to 4.2 (± 0.8) for LIV group. At Instruments Handling, LIV group performs better than MIV group: participants obtain on average a score of 3.6 (± 0.5) while participants in MIV group obtain on average 3 (± 0.5). At Knowledge of Procedure, participants in MIV group obtain on average a score of 3.6 (± 0.7) while participants in LIV group obtain a score of 3.1 (± 0.7) (fig 4.7).

Ten participants were able to send evaluations of the first and second C-Sections performed during their first internship as a Resident in gynecology-obtetrics. Among these 10 participants, 5 had been trained with LIV and 5 with MIV. Between first and second C-Section, the two groups, on average, increase their performance: group LIV increases their score of 0.35 (± 0.7) on average and MIV group of 0.39 (± 0.8) on average. Group LIV progresses essentially on knowledge of procedure (+0.8 ± 0.8) and flow operation (+1 ± 1.7) but with important variability between participants. MIV group progresses on knowledge

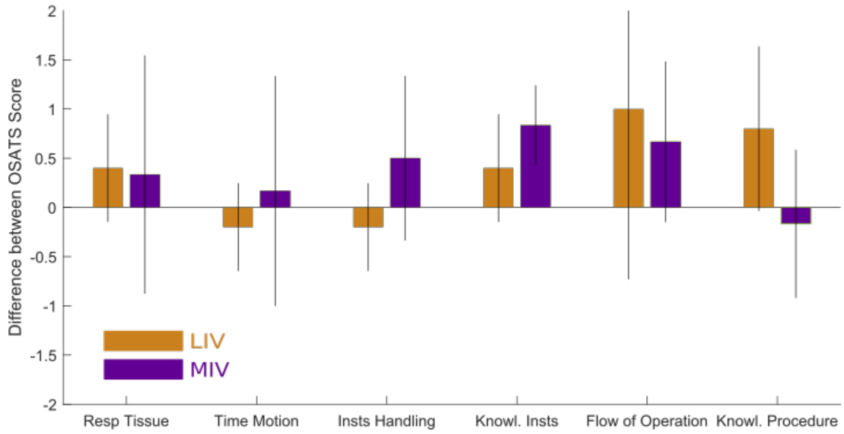


FIGURE 4.8: Mean difference in OSATS Score between 1st and 2nd C-Section for participants in group Less Informative Videos (LIV), n=5 and participants in group More Informative Videos (MIV), n=5.

of instruments (+0.8 ± 0.4) with relatively small variability between participants, on instruments handling (+0.5 ± 0.8) and flow of operation (+0.6 ± 0.8) with important variability between participants (fig 4.8).

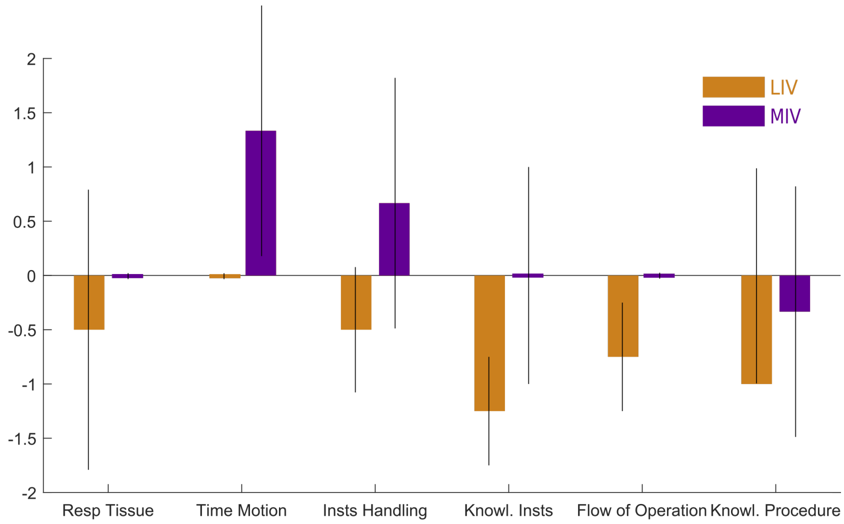


FIGURE 4.9: Mean difference in OSATS Score between 2nd and 3rd C-Sections for participants in group Less Informative Videos (LIV), n=4 and participants in group More Informative Videos (MIV), n=3

Seven participants sent evaluations of their first, second and third C-Section performed during their first internship as a Resident in gynecology-obstetrics. Among them, 4 were trained with LIV and 3 with MIV. On average, participants in LIV group decrease their score on every variable of the OSATS except for time and motion where a stagnation is observed with a mean of -0.6 (± 0.4) for all variables confounded between second and third evaluation. Participants in MIV group progress on time and motion (+1.3 ± 1.15) and instruments handling (+0.6 ± 1.15) but results differ greatly between participants (fig 4.9).

4.2.4.2 Secondary Research Question

Participants' experience depending on the media used to view the videos

When comparing participants' satisfaction for PC and VR, combining participants in LIV group and participants in MIV group (cf. fig **??**) no significant differences are observed for each of the questionnaire factors between PC and VR, except for Novelty significantly better rated by participants when viewing the videos in VR (Wilcoxon signed rank test, Z=276 $p<0.001$).

The same pattern is found for group LIV, with only Novelty being significantly different between PC and VR (Wilcoxon signed rank test, Z=55.5 $p<0.001$) as well as for group MIV which also rates Novelty significantly better when viewed in VR compared with PC (Wilcoxon signed rank test, Z=1065, $p<0.001$).

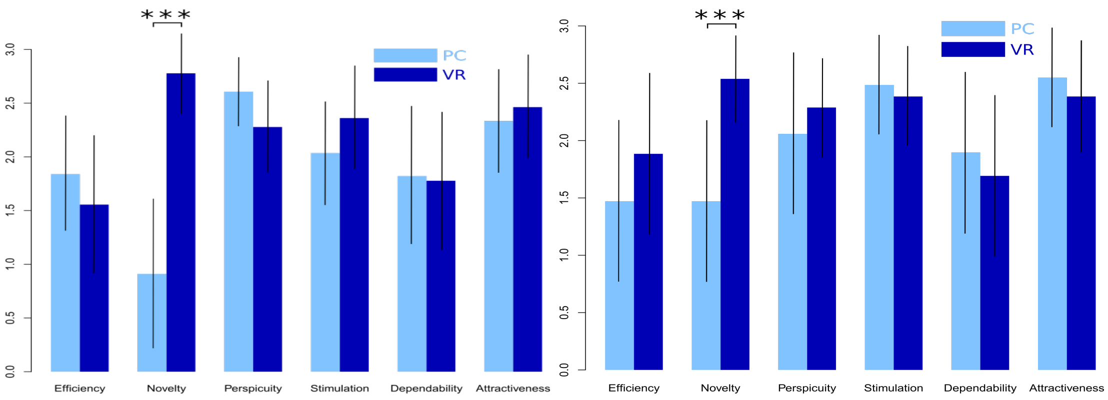


FIGURE 4.10: *Left:* UEQ after viewing the LIV on PC (n=12) and in VR (n=12). The difference is significant for Novelty between PC and VR, (Wilcoxon signed rank test, Z=55.5 $p<0.001$). *Right:* UEQ after viewing the MIV on PC (n=16) and in VR (n=16). The difference is significant for Novelty between PC and VR, (Wilcoxon signed rank test, Z=1065, $p<0.001$)

While not significant, group LIV rates efficiency, perspicuity and dependability better on a standard PC screen compared with VR. Mean score for efficiency on a PC is 1.8 ± 1 vs. 1.5 ± 1.2 in VR, mean score for perspicuity on a PC is 2.6 ± 0.9 vs. 2.4 ± 0.7 on a PC vs. 2.3 ± 0.9 in VR, and mean score for dependability is 1.8 ± 1.2 on a PC vs. 1.6 ± 1.2 in VR. Simulation is better rated in VR (2.3 ± 0.9) than on a PC (2 ± 0.9), same as attractiveness: 2.4 ± 0.8 in VR vs. 2.3 ± 0.8 on a PC (cf. fig 4.10). Group MIV rates better stimulation, dependability and attractiveness on a standard PC screen compared with VR. Mean score for stimulation on a PC is 2.4 ± 0.8 vs. 2.3 ± 0.8 in VR, mean score for dependability is 1.9 ± 1.1 on a PC vs. 1.6 ± 1.3 in VR and mean score for attractiveness on a PC is 2.5 ± 0.6 vs. 2.3 ± 0.8 in VR. The differences are not significant. At the opposite, efficiency and perspicuity are better rated in VR compared with PC. Mean score for efficiency is 1.5 ± 1.2 vs. 1.8 ± 1.2 in VR and mean score for perspicuity is 2 ± 1.1 on a PC vs. 2.21 ± 0.8 in VR (cf. fig 4.10).

4.3 Discussion

4.3.1 Primary Research Question

Regarding clinical knowledge on procedure, while participant's level in both groups is equivalent before video training, differences are observed after video training. In group LIV, participants that were weaker before training progressed after training, but remained among the weaker participants. The participants that were the stronger before training progressed in an equivalent proportion compared to the weaker. In group MIV, participants that were among the weaker before training made proportionally better progress than participants who were the stronger before training, in such a way that they have as much knowledge on the C-Section after training, as those who were the stronger.

This result, although insufficient in itself to demonstrate superiority of surgical training inspired and created from human learning theories and models, still demonstrates that using such framework positively impacts the amount of knowledge detained of the procedure by surgical students, in such a way that they reach an almost equivalent level, with little effect of their initial knowledge. Yet, will the amount of the initial knowledge does not predict the amount of knowledge that will be achieved when training with the techno-pedagogical video-based training, other factors must as disparities remain between the participants after training with the MIV. Our experiment does not succeed in identifying these factors, and we strongly encourage future research on the matter.

The results obtained on technical skills should be considered with caution, as time constraints and the priority of care over the experiment induced biases: each participants were rated by a different expert, in a different hospital. The intervention difficulty, and the expert subjectivity may have strongly influenced the results. Also, the results are obtained on a small number of participants. However, all precautions taken, a small tendency is observed in the data. Participants who were trained with the MIV tend to score better than participants trained with the LIV, for their first C-Section as a resident, on respect for tissue, time and motion, flow of operation and knowledge of procedure. They score equivalently than group LIV on knowledge of instruments, and they only do worse in instruments handling. Also, participants in group MIV tend to increase their performance on time and motion handling, instruments handling, knowledge of instruments and flow of operation from their 1st to their 3rd C-Section, while participants in group LIV do not overall increase their score from the 1st to the 3rd C-Section.

Due to the technical constraints mentioned earlier, it is very difficult to measure how the pedagogical framework of the video-based training influences technical skills of 1st year residents, hence the results obtained on this matter are only exploratory. Still, they tend to show a positive impact of the pedagogical framework used in the MIV on the skills in the OR, and while this tendency does not corroborate any hypothesis, it encourages further research to identify better the direct consequences of creating training videos for surgery within a theoretical pedagogical framework. Future research could investigate how the gesture quality is improved as a consequence of the explicitation problems, the operators, the rules of action and the control actions in the surgical learning, all elements with constitute the learner's conceptions. It would also be interesting to investigate whether the knowledge developed through training with the MIV are applicable to participants not only to different clinical cases of C-Sections, but also to other surgical interventions, as the cKç human learning aims to do.

4.3.2 Secondary Research Question

Only small differences are observed in terms of User Experience as measured by the User Experience Questionnaire (UEQ). An exception is observed for Novelty. Still, when looking scores given by each group of participants, LIV and MIV, at the UEQ for PC and VR, distinct differences emerge. Participants who viewed the LIV were more sensitive to the novelty of the HMD (Wilcoxon signed rank test, $Z=55.5$ $p<0.001$) than those who viewed the MIV. Group LIV also better rated attractiveness in VR compared with PC. At the opposite, LIV gave a worse score for efficiency, perspicuity and dependability in VR than on PC. Group MIV also better rated novelty when viewing the videos in VR compared with PC (Wilcoxon signed rank test, $Z=1065$, $p<0.001$), but the difference in score is much smaller than for group LIV. Group MIV, contrarily to group LIV rated better efficiency and perspicuity in VR compared to PC, but all other factors have a worse score in VR compared to PC. Tendency is inverted between the two groups for efficiency, perspicuity, stimulation and attractiveness, showing an influence of the videos content on the user's experience when using different visualization devices for a surgical training video.

Group MIV, who developed knowledge in a more equitable way, also seems to find the VR helmet visualization less easy to get familiar with, less predictable, less attracting and less stimulating, but more efficient. Group LIV, who developed knowledge less consistently than group MIV, was also more sensitive to the novel aspect of the VR helmet visualization, to its stimulating and attracting aspect, but found it less easy to get familiar with, and less secure and predictable. The results suggest that, when watching a pedagogical and didactic video, the technological aspect becomes less appealing. This observation is in contradiction with what was expected based on the Technological Content Knowledge (TCK), which may have been incomplete. Indeed, while several studies proved VR to draw enthusiasm [71; 70], to increase the degree of involvement in the task [159], no study to our knowledge has focused on the impact of immersive VR on the augmentation of clinical knowledge or skills in surgery. Hence the results obtained add to the existing Technological Content Knowledge (TCK). More research should be conducted on other surgical interventions, using different human theories and models, and different visualization means.

4.4 Conclusion

The results obtained confirm the impact of a theoretical pedagogical framework for a C-Section training video on participants knowledge, showing +10% improvement in MCQ score for group MIV after training compared with group LIV. This result, while seemingly obvious, is too frequently ignored by surgical trainers when provide surgical videos to residents. The greater positive impact of the MIV on the surgical students knowledge compared with the LIV is probably due to the fact that the creation of the video is based on relevant Pedagogical Content Knowledge (PCK). The PCK lies at the intersection between pedagogical practices and learning objectives: in our case it represents both the adequate way to display the learning material to medical residents for the C-Section, and the the way to select the adequate learning material itself, needed by the medical residents to understand and reproduce the surgical gesture without errors.

Without this knowledge, the training video only displays the gestures in a linear manner and it is up to the learners to extract the know-how, the expertise that lead to the achievement of the gesture. Yet this information is both complex and essential [21]. Video-based learning tools are often not efficient as the content they use is rather demonstrational than pedagogical, mainly focusing on non-technical skills and lacking multimedia design principles [142]. Furthermore, these videos do not provide learners with the implicit and tacit rules acquired during years of surgical practice and which constitute the surgical know-how [99]. These results are consistent with works by [120] for inpatient rounding experience, which showed the positive impact of an instructional design (the 4 Components of Instructional Design) for supporting learning videos content on learners long term knowledge.

To our knowledge, there are not existing work on the impact of a pedagogical video for gynecologic surgery on residents technical skills. The results presented in this article can hardly be generalized and do not corroborate a hypothesis, but still pave the way for future research, confirming or informing the tendency observed here: a positive impact of the pedagogical video on the residents surgical skills, at least in terms of respect for tissue, management of time and motion, respect of operation flow and knowledge of procedure as well as an appeal and appreciation of technology that is dependent on the content displayed through this technology.

Indeed, the participants experience when visualizing the videos, either LIV or MIV, on a standard PC screen or in a VR helmet, is interestingly almost completely opposed between the two groups. The technology is more appealing when the video is less instructive and vice and versa. Here the Technological Content Knowledge (TCK) seems to play an important part on the participant appreciation of the training received. When the learning objectives are better met, *i.e.* for the group MIV, then the newest technology, the VR headset, is rated less novel than by group LIV. Group MIV also rates the VR headset less stimulating, less predictable and less attractive compared with standard PC. At the opposite, group LIV who viewed the video where the learning objectives where not met, found the VR headset more stimulating and attractive than the standard PC.

These results are opposed to what was expected, based on the literature found on VR headset training in surgery [124; 84; 60]: while rated both by group MIV and LIV as more novel than the PC standard screen, the VR headset does not seem to improve the experience of the video-based training, and the most important factor seems to be the quality of the learning material, with group MIV rating the training as very stimulating and attracting on a standard PC screen. Yet, the system still lacks efficiency, intuitiveness and predictability, which are purely technological aspects needed to be worked on. These results, as well as those found in [132], encourage more consideration for learning theories in the development of VR applications, more consideration for each technology strengths and limitations, showing their importance not only regarding knowledge acquisition of the user, but also her/his experience *i.e.* interest and motivation for using the VR application. Finally, it supports the conception of learning scripts including all dimensions covered by TPACK that guide the creation of learning scenarios towards the target competencies, used in real scenarios, and using adequate technologies.

However, the study presented here has different limitations, namely the limited number of participants leading to a heterogeneous set of data regarding the technical skills, the absence of long-term evaluation of knowledge or of the impact of the visualization device on the knowledge and skills developed by the participants, the absence of results on the influence of the video duration on the participant experience, the absence of evaluation of the MIV impact on development of skills on other surgical intervention that require the same knowledge as the C-Section. The results encourage future studies, involving other learning theories, other visualization devices, and stronger evaluation of either technical or non-technical short-term and long-term skills in the OR.

4.5 Contributions of the chapter

In this chapter, we present techno-pedagogy, as well as a study on the influence of a techno-pedagogical framework (TPACK) for the creation of a video-based training on: the evolution of the knowledge held by the medical residents on a surgical procedure, the evolution of their skills, and their experience and appreciation of the training. The study is conducted under real learning conditions with 1st year medical residents which gives it an undeniable value. The data are scarce but they are extracted in real conditions and not in a partial and distorted reproduction of the reality.

Additionally, the experimental protocol aims at highlighting hybrid pro-cesses, at the intersection between technology and learning, which is different from what is usually found in the literature: a focus either on technology, or on learning. The results obtained are in support of a greater attention given to the pedagogical content of surgical training -which might be guided by pedagogical frameworks such as the TPACK-, at least as important as the attention given to the technological features. This statement is in line with the observations made in the first and second chapters, that the creation of a surgical training should be motivated and framed by the residents expectations, needs, constraints and previous skills. That is to say that the training module should be designed to target the development of skills and knowledge that are transferable to the real world and not module-dependent, too specific or broken into too small parts for it to make sense in a real life situation. Here this was made possible by the use of the TPACK framework that lead to the human learning model ckcç. However, the limitations of this experiment are the same as its strengths: the too small number of data does not allow to corroborate a hypothesis with certainty. The experiment is empirical, and we plan to continue the research in a more methodological way, on the basis of the results primarily obtained.

Chapter 5

Conclusions and Perspectives

Surgery is a highly demanding activity that requires years of training, to learn the very diverse and complex skills that compose it. The words of Jean-Louis Faure, a surgeon during the 20th century, describe it nicely:

"../..pour avoir le droit de pratiquer l'opération, pour avoir le droit d'exécuter sur son semblable cet acte sans appel qui porte avec lui la vie et la mort, il faut savoir! Oui, pour pouvoir travailler dans la chair de l'homme d'une main qui ne doit connaître ni l'hésitation ni la défaillance, il faut avoir la conscience profonde du droit que l'on a de l'entreprendre ; il faut avoir au fond de l'âme cette certitude, ou plutôt cette conviction, que l'on sera à la hauteur de sa tâche, et cette conviction, c'est une sévère éducation antérieure et une longue préparation qui peuvent seules la donner !" [44]

Having the right to perform surgery is *being profoundly conscious* of the ability to it. The ability is only given by *knowledge* acquired through *education* and *lengthy preparation*. Contrary to what is generally thought, the surgeon does not only operate with her skillful and dexterous hands, but first and foremost with her head: her knowledge, education, expertise.

This lengthy training is now hindered by time and administrative constraints, and by the fact that the number of tools accessible to the surgeons keeps growing, forcing them to master increasingly varied skills, on technological systems that are rather technological achievements, and expert assistance than pedagogical achievements or learning assistance. In this sense, the key to the alarming number of medical residents abandoning the surgical speciality does not seem to be on the side of technological innovation alone, but on the side of technological innovation within a pedagogical and didactic theoretical framework. This theoretical framework may prove to be an indispensable tool for linking any system intended to be used for surgical education, or for improving surgical performance, with its users: their expectations, their previous skills, and as a consequence the systems attractiveness, understandability, usefulness, utility, completeness, etc.

In this thesis, after having introduced the difficulties faced by medical residents in their surgical training in 1 we have investigated in three different ways to work on concrete levers for facilitating surgical learning.

In chapter 2, today's surgical robotics were presented, and especially one type of surgical rootics: comanipulation. This type of robotics, aims at augmenting the dexterous performance of the user without forcing her/him to re-learning another technique than the classic one, or forcing the medical team to rethink the way it works. We have developed an experiment that aims at studying whether robot-assisted laparoscopic surgery (RALS), when controlled in a comanipulated manner still contributed to training hand-eye coordination skills in classic laparoscopic surgery (CLS), in the same way than training in CLS. The protocol and its results demonstrate that contrarily what was demonstrated in previous work for telemanipulated surgery, comanipulated surgery did not negatively impact hand-eye coordination skills in CLS and even developed them in the way as when training in CLS. This chapter answers the problematic addressed in this thesis by proposing a technological advanced system for surgical training which does not put technology at the center of its concerns but rather the user, and thus ensures the complementarity and continuity of learning: rather traditional or related to new technologies.

However, this study presents several limitations, notably regarding the too little number of exercises which do not represent the complexity of a surgical procedure, and the limited number of participants. These internal limitations of the study invite to conduct similar studies using other surgical robot, a greater number of exercises and more participants. However, other and more important limitations can be stressed: while the thesis encourage pedagogical approaches for surgical education, this study lacks consideration for an important aspect of what pedagogy is, literally. Pedagogy refers to the consideration of theories of learning, understandings of students and their needs, and the backgrounds and interests of individual students for educators to make their actions, judgments, and other teaching strategies. The study presented lacks consideration for what composes the surgical gesture: the knowledge. By training residents with exercises of laparoscopic surgery which train exclusively the technical skills (dexterity, hand-eye coordination) the great majority of what makes surgery proficiency is forgotten. It is this observation that led us to conduct the second study, presented in the following chapter.

In chapter 3, video-based learning for surgery is presented, as well as the knowledge representations in surgery which may serve to create the videos. An investigation carried with medical school residents is presented, which aims at elaborating the existing links between pedagogy, video-based learning and surgical education. The approach is very different to the study presented in the first chapter, both in the research questions raised and in the methodology used. The study is exploratory and aims firstly at identifying more precisely and in a more concrete way the difficulties faced by medical residents when training for surgery, as well as the consequences of these difficulties. Secondly, the objective of this study was to determine how a video-based training whose creation is based on a model of human learning, the ckç, impacted these difficulties. In this chapter, the creation of the video on the basis of the human model is presented, as well as the video itself. The methodology, contrarily to the study previously presented, is qualitative, because the expected results are complex and individual-dependent. Interviews are used, which aim at bringing out a reality that is unknown to the experimenters before starting the study, and that is constructed in the exchanges between the interviewers and the interviewee.

The interviews enabled to bring out different themes which characterize both the difficulties faced the medical residents when training for surgery, and the way the pedagogy-based video made it possible to overcome some of these difficulties, and not others. The themes observed are the following: the way *practice gives learning a meaning and a necessity*, the fact that *the best learning scenario lies in the repeated succession of the pedagogical video and practice*, that *acquiring knowledge with the pedagogical video results in a better sense of belonging* and finally, the comprehension, thanks to the video of *operative invariant* between different surgical procedures. All these themes amount to saying one and the same thing: there exists a *complementarity and influence between the pedagogy-based video and the OR*. The pedagogy-based video has enabled to revealed knowledge that otherwise remains unknown to the medical residents, while the OR plays an important part in creating the need to learn, the understanding of the ultimate reasons for performing the surgical gesture etc. These themes addressed allow us to affirm with more certainty that to increase the knowledge of interns on the surgical gesture on the one hand, and to increase their feeling of belonging to the medical team on the other hand, technological advancements are not needed as much as pedagogical advancements in surgical education.

However, this study presents some inherent limitations, which reside in the individuality of the testimonies collected, and in the absence of consideration for an important part of surgical training: the technological means to expose it.

This brings us to chapter 4 were we present techno-pedagogy, which in short means considering both pedagogical and technical aspects in one's teaching practices. In this chapter we introduce a techno-pedagogical framework, the Technological Pedagogical Content Knowledge (TPACK) on which we base the creation of a video-based training for the C-Section. The creation of this video-based training is presented, as well as its impact on the medical residents knowledge, skills and experience depending both on the training *pedagogical content* and *technological mean to display it*. Indeed, the video-based training with which medical residents are trained during the protocol is either build following the classification of a human learning model -presented in the chapter-, the ckç, or rather demonstrational, following no specific pedagogical framework. Additionally, the video-based training is presented to residents both on a standard computer screen and in a Virtual Reality (VR) helmet. The results presented in this chapter show the positive impact of the pedagogical framework on the resident's knowledge and tends to show the same impact on the residents skills, but data are missing to make statistical comparison. Regarding the impact of the technological device used to display the video on the residents' experience, it varies greatly, depending not on the level of technology (high or low) but on the level of pedagogy of the training. That is to say, the level of pedagogy of the training has a greater importance in describing the resident's experience than the technological mean to display the video. These results are also consistent with the assertion that the training content is crucial in surgical education.

However this study does not allow to affirm it with certainty, nor does it allow to know which type of technology better conveys which type of knowledge in surgical education. Hence the fact that the chapter is entitled *"towards techno-pedagogy"* rather than *"a techno-pedagogical training"*. These results also encourage the conduct of more methodological protocols as opposed to empirical protocol proposed in this thesis.

On the basis of these different results, we can now present directions for future research. In the future, I would like to continue research on pedagogy and surgical education in different ways. First, we would like to study more broadly how models such as the ckç applies to different surgical interventions, in different domains, different locations and different clinical cases. This would require a meticulous study of the surgical activity through systematical analysis of surgical films, observations in the OR, as well as interviews with experts and learners. All of these probably from a sociological and anthropological as well as psychological point of view. Indeed, surgical training is not a solitary activity, it is an activity that is carried out by a group of people in which each person has a specific role to play affected by sociological, historical and psychological variables. All of these variables require time to be understood, as well as their influence on every individual's performance. They are likely to have a strong impact on the adoption or the abandon of any surgical training no matter how good it may be from a purely pedagogical point of view. The result would be a formalization of (1) surgical knowledge (steps, instruments, risks, anatomy), (2) technical skills (dexterity: pressure, force, angles) and (3) non-technical skills (decision making, plan formulation, communication, teamwork, leadership) related to the surgical interventions.

This detailed study of different surgical procedures would be completed by a study on the way specific skills and knowledge are conveyed by specific technological means (videos, VR helmets, surgical robotics). We mentioned before that a robot did not have the ability to train medical residents on the knowledge required to perform any surgical intervention. Neither does a video have the ability to teach medical residents the technical skills to perform surgical interventions. A better understanding of what connects the skills and knowledge to perform surgery, and technology is necessary. Experimental protocols could for focus on: the study of the steps of surgical training at which are comapinulated robotic arms are the most useful; the study of the elements of a surgical intervention from a pedagogical point of view (taking into account the learning variables: rules of action, operative invariant) who are of interest to be seen in a VR headset; the study of those who are of interest to be seen on a video and practiced with comanipulated robotics arms, etc.

This would lead to analyzing how human learning models applied to surgery may be linked with relevant technological systems, so that the technical characteristics of the system are best put to use depending on the elements found on the model, and the skills targeted.

This would enable the creation of a techno-pedagogical framework for (1) capturing, (2) structuring and (3) visualizing learning scripts in surgery. For capturing, the framework would characterize technology (e.g., stereo cameras, sound recording, image definition requirements, motion capture systems) and methods (e.g., how to capture the room or surgeons' point of view) to record the pedagogical elements identified in the empirical study; for structuring, the framework would characterize how to choose and arrange footage, as well as determine which elements are missing (such as instruments, robotic arms etc.) and how to add them to the script, so that learners acquire given concepts. For visualization, the framework would describe how to display the elements selected, rooting on multimedia and interaction design principles. The arrangement of these different resources would not be linear, each element contributing the inform the other elements while still guided by human learning models and theories.

This framework would then have to be evaluated, through a study with attending surgeons to capture and produce pedagogical videos, and with residents to visualize surgeries for learning, measuring its impact on learning outcomes compared to classic demonstrational training. Outcomes would reflect the knowledge, technical and non-technical skills acquired and their evolution. Despite the logistical difficulties involved, to achieve strong outcomes in surgical education, this evaluation would have to include numerous attending surgeons, and test their abilities under real conditions -in the OR, or in high-fidelity settings. Finally, in my opinion, it is important to emphasize the contribution of human and social sciences theories and methodologies in the creation and conduct of the proposed future research project, which would take place in a rather technology-oriented environment, to medical education, technology, and to their own domain. This human and social sciences approach, by contributing to giving a stronger meaning to technologies developed in the field of medical education, is important to me.

Appendices

Appendix A

Model of hysterectomy

Activity	Actions, goals and anticipations	Rules of action, information gathering, controls	operational invariants	Intervention domain
Pre-operative check	1.Check the identity of the patient: name, first name, date of birth			
	2. Recall the planned procedure (validated with the patient and the team): adnexectomy or not			
	3. On the anaesthesia side: Check that all documents are available (allergy, stop certain treatments, fasting, antibiotic prophylaxis...)			
	4. On the surgical side: Check that all documents are available: imaging, anapathy, conclusion of surgical staff, conclusion of multidisciplinary consultation meeting			
	5. Check the material: A box of adapted instruments, retractors, an electric bistoury, +/- complementary energy: ligasure forceps, other..., bladder probe, fields			
1. positioning of the patient	1. place the patient in supine position, arms at 90°, double shift position (legs apart)			
	2. Prepare the vaginal cavity with Betadine before starting the surgery			
	3. Incise the peritoneum			
	4. Set up the sterile fields (nipple, pubic symphysis, anterior superior iliac spines laterally free)			
	5. Place an indwelling bladder catheter to ensure constant bladder drainage	Keep the bladder empty This is important for safety		
	6. Generally, the surgeon places himself/herself on the left side of the patient			
2. Incision and inspection	1. incise the abdominal wall transversely, 3 cm above the pubic symphysis (Pfannenstiel incision)			
	2. Incise the fascia of the rectus abdominis muscles			
	3. Incise the peritoneum	Be sure to follow the centerline	The midline as well as the longitudinal incision is the standard reference for pelvic surgery, to facilitate the surgical procedure and avoid damage to other vital structures.	

	3.1. Perform a transverse incision			
	4. Carefully lift the intestines and hold them in wet fields			
	5. Install the spacer	Examine the uterus, surrounding organs and check for abnormalities and/or adhesions	Restoration of the pelvic anatomy by release of adhesions is mandatory for a safe operation	
3. Opening of the peritoneum and exposure of the round ligament	1. Place the Kocher clamps	Check that the point of the forceps is in the avascular and transparent space of the anterior and posterior broad ligament, and does not reach the uterine vessels below	Usually, Kocher clamps are placed between the uterus and the "appendix".	
	2. Hold the uterus in traction contralateral to the area of surgery	Identify the round ligament		
	3. Grab the round ligament on the right side and lift it using forceps			
	4. Insert the needle twice with 1-0 absorbable sutures			
	5. Tighten and cut between the ligatures with scissors	Identify the starting point for the vesico-uterine incision: lift the broad ligament up and identify the vesico-uterine fold. (Usually the target is 1cm down from the lower end of the uterine serosa). → "If you locate the target termination point for the incision (i.e., the starting point for the next incision) then you decrease the risk of performing overly deep dissections that can induce bleeding." Be sure to stay superficial in the dissection: "if you stay superficial, then you avoid any bleeding."	When cutting ligaments or vessels, it is important to put the scissors perpendicular to the ligament. After sectioning, air will enter the retroperitoneal cavity, the loose connective tissue will fall out, and the cavity will be seen	
4. Opening of the broad ligament	1. incise the anterior leaflet of the broad ligament	Be sure to stay superficial in the dissectionIf you stay superficial, then you avoid any bleeding	Dissections that are too deep into the bladder can lead to bleeding or bladder injury.	
	2. Lift the broad ligament upward to identify the vesico-uterine fold.			
	3. Lift the broad ligament with forceps, and detach all subperitoneal connective tissue with scissors		Generally the target is 1cm down from the lower end of the uterine serosa	
	3.1. Perform a peritoneal opening	If the uterus is not very mobile, the peritoneal opening makes it possible to obtain much greater mobility		When the uterus is not very mobile
	4. Make a concave incision line from the round ligament to the vesico-uterine fossa			
	5. Incise the thin transparent peritoneum to the target			
	6. Continue the incision of the central leaflet of the broad ligament cranially parallel to the lumbo-ovarian ligament			
	7. Pull the peritoneum strongly, then attach the scissors almost vertically to the peritoneum, push lightly and then scrape down all the connective tissue under the peritoneum.	If you methodically carry out these gestures, then only a transparent and fine peritoneum remains which can be incised without bleedingIf the connective tissue is poorly detached, veins and capillaries remain on the side of the peritoneum, and the incision ends in bleeding.		
	7.1. Perform the same procedure			in case of detachment of the ureter, bladder, and rectum to the surrounding tissue
5. Location of the ureter and section of the lumbo-ovarian	1. Dissect loose connective tissue and incise toward the lumbo-ovarian ligament			

	2.Identify the ureter		The ureter is visualized on the posterior peritoneal leaflet of the broad ligament. When stimulated with the finger, a "snake-like" peristalsis movement is visualized. The ureter is identified crossing the iliac vessels before any gesture on the lumbo-ovarian ligament. This allows identification of the needle insertion point at a distance from the ureter.	
	2.1. The incision of the lateropelvic peritoneum is extended parallel to the lumbo-ovarian ligament.	The external iliac artery is then identified on the medial part of the psoas muscle.		When the identification of the ureter is difficult
	3. Insert the needle away from the ureter			
	4. Ligate the ligament and cut it			
	5. Strongly pull the peritoneum and then attach the scissors almost vertically to the peritoneum, push lightly, and scrape all connective tissue below the peritoneum	Determine the end point of the incision	the termination point of the incision is the uterine origin of the sacro-uterine ligament.	
	6. All of the above steps are performed for the left-sided round ligament, the broad ligament, the lumbo-ovarian ligament or appendix			
6. Bladder detachment	1. Mobilize the bladder: begin mobilization at the midline of the cervix	Before mobilizing the bladder, palpate the cervix from the anterior and posterior sidesIf you palpate the cervix, then this will allow you to check its position	The bladder frequently drifts laterally due to fibroids or adhesions. Palpation is also essential to estimate cervical length.Second, mobilizing the bladder prevents bleeding from the lateral vesico-uterine ligaments.	
	2. Lift the anterior leaflet of the severed broad ligament		When the surgeon lifts the anterior layer of the broad ligament, the vesico-uterine space opens spontaneously where the first incision should be made, in the center of the cervix.	
	3. Push the scissors vertically to the cervix and cut the connective tissue	Identify Halban's fasciaIf you push the scissors vertically at the cervix and cut the connective tissue, then this will reveal Halban's fasciaCheck for fatIf you encounter fat, then change the route. Encountering fat is the dissection coming too close to the bladder.	Halban fascia is white, soft and shiny. The fat belongs to the bladder. Its presence indicates that you are not in the right plan.	
	4. Dissect the connective tissue downward using scissors from the cervix completely to the lower end of the cervix	Make sure that the dissection is not hemorrhagicIf the dissection is hemorrhagic, care must be taken to find the correct plane, in contact with Halban's fascia, for an exsanguinated dissection.	The bladder is now mobilized to the appropriate height, about 1cm below the vaginal cul-de-sac.	
		If you observe bleeding, you are not in the right plane.	The vesico-vaginal space is avascular	
	5. Loose connective tissue on the surface of the ligaments is carefully removed			
	6. Place the retractor over the detached portion, pushing the bladder down			
	7. Carefully dissect and remove connective tissue from the uterine artery and vein 8. Also remove connective tissue from the vesico-uterine ligament	If you remove the connective tissue on the vesico-uterine ligament, then you avoid ureteral injuries		
7. Ligature and section of the uterine pedicles	1. Skeletonize the ascending branches of the uterine artery and veins			

	2. Keep the uterus in an upward pull and push the bladder down using the retractor	Feel the ureter running along the posterior leaflet of the broad ligamentIf you know the position of the ureter, then you limit the risk of injury	It is possible to identify the level of the ureter that enters the cardinal ligament 1 to 3 cm lateral to the cervix and 2 to 4 cm below the uterine artery	
	3. Cut the cardinal ligament twice including the uterine artery and veins until you reach the vaginal cul-de-sac			
	4. Place a first Jean-Louis Faure forceps, concave upwards at a 90° angle to the upper part of the cervix so that the tip of the forceps arrives 1cm below the height of the internal os of the uterus			
	5. Place a second forceps along the cervix for hemostasis of the small ligament veins	Check that the clamped side of the forceps is outside the surface of the cervixIf the clamped side is outside the surface of the cervix then all vessels will be fully clamped		
	6. The tip of the forceps reaches the level of the vaginal cul-de-sac, then the lower half of the cardinal ligament is cut and sutured.	Recognize the plane that demarcates the cervix from the ligament.	Once this plane is reached during the section of the cardinal ligament, especially near the utero-sacral ligament, it is possible to feel confident about the cutting. The cut has finally reached the vaginal cul-de-sac.	
		Avoid cutting too deep into the paravaginal tissue.If you cut too deep into the paravaginal tissue, it may result in a significant amount of bleeding.	To avoid injury to the ureter during the cardinal ligament ligation, the use of two forceps is essential. Each step moves the ureter laterally to the cervix and vagina, which is safer than using only one clamp. The surgeon can feel the course of the ureter at any time during the surgical procedure and should confirm the distance between the ligature and the ureter.	
	7. Perform these steps on the left side		Generally, it is not necessary to cut the utero-sacral ligament which will be cut simultaneously during the amputation of the vagina	
	8. Place a vaginal valve or mounted pad in the pouch of Douglas, and palpate the transitional area between the cervix and vagina			
	9. Insert the scalpel vertically into the highest portion of the anterior wall of the vagina			
8. Vaginal opening	1. Prepare the portio and vagina with povidone-iodine			
	2. Insert a mounted tampon or vaginal valve into the vaginal cavity			
	3. Place the long, straight Kocher forceps sequentially at the end of the vagina for hemostasis			
	4. Cut and tie the utero-sacral ligament with the vaginal wall			
	5. Close the vaginal dome with separate X-stitches at the corners, then separate X-stitches or overjet of the vaginal slice	Be sure to place the curved forceps along the vaginal cul-de-sac.If the curved forceps are placed along the vaginal cul-de-sac as a landmark, then it is easier to cut the vagina with the scalpel or scissors along the curve of the forceps.Be sure to make a careful suture at the lateral end of the vagina, near the tip of the cardinal ligament.		
	6. Clean the retroperitoneal space with warm saline solution	Confirm the absence of bleeding and foreign bodies		

9. Closing the abdomen	1. Check the gauze count			
	2. Suture the pelvic peritoneum with continuous 2-0 sutures and close it completely			
	3. Remove the retractor and gauze and return the bowel to a normal position			
	4. Close the abdomen by suturing the peritoneum, fascia, and skin			

Appendix B

Interview before training with the video of hysterectomy

Pre-Training Interview

Participant n°	
Interviewer	
Intern Year	
Hospital	

[Infos]

Stage de chirurgie en mai (oui/non) :
Ok pour enregistrer le zoom (oui/non) :
Intéressée par spécialisation en chirurgie (oui/non) :

Your experience of surgical learning

1. Can you tell me how you learnt to perform surgery? With what material ?
   Pouvez-vous me dire comment est-ce que vous avez appris et continuez d'apprendre à faire de la chirurgie ? Avec quel matériel ?

2. Which of these material do you use most? Why? The less? Why? Lequel de ces matériaux utilisez-vous le plus ? Pourquoi ? Le moins ? Pourquoi ?

Your experience of learning hysterectomy (or the last surgery seen/performed if very few hysterectomies were seen or performed)

3. Can you tell me how much you know on hysterectomy? How far do you feel from being able to perform a hysterectomy?
   Pouvez-vous me dire ce que vous savez à propos de l'hystérectomie ? A quel point est-ce que vous vous sentez éloigné.e de la capacité de réaliser une hystérectomie par vous-même ?

4. Can you tell me how many hysterectomies you have seen? Have participated to ? With what role ?
   Pouvez-vous me dire combien d'hystérectomies vous avez vues ? A combien d'hystérectomies vous avez participé ? Avec quel(s) rôle(s) ?

Figure B.1: Interview before training

5. Can you tell me about the last hysterectomy you saw? Do you remember it ? Pouvez-vous me parler de la dernière hystérectomie que vous avez vue ? Vous en souvenez-vous ?

6. Can you tell me how much of the procedure you understood approximately? What did you most understand (instruments, steps, risks, anatomical structures)? Pouvez-vous me dire combien de la procédure vous avez compris environ ? Quels aspects avez-vous compris (plutôt les instruments, les étapes, les risques, les structures anatomiques) ?

7. Parts of the procedure you understood, did they make you think of the learning material you have used for hysterectomy? What material ? Les aspects de la procédure que vous avez compris vous ont-ils fait penser aux matériaux d'apprentissage que vous utilisez ? Quels matériaux ?

8. Why do you think that this procedure, this moment made you think of the learning material? Pourquoi pensez-vous que cette procédure, ce moment vous a fait penser au matériel d'apprentissage ?

9. Can you describe elements that you did not understand? Pouvez-vous me citer des éléments que vous n'avez pas compris ?

10. Did you not know for this specific case or do you not know generally? Ce manque de compréhension était-il lié à ce cas en particulier ou bien est-il général ?

11. Do you know what these shortages are due to (you do not have enough experience, it is an omission of your mentors, it is a feeling of their part that this is useless to know, this knowledge is difficulty to teach) ?
Savez-vous à quoi ces manques sont-ils dus (vous n'avez pas assez d'expérience, vos mentors

Figure B.2: Interview before training

oublie de vous enseigner ces connaissances, ils sont le sentiment qu'elles sont inutiles à maîtriser, elles sont trop difficiles à enseigner) ?

Your suggestions

12. Would you consider that your surgical education could be improved, both in the classroom and in the OR?
    Considérez-vous que votre formation chirurgicale pourrait être améliorée, à la fois dans les salles de classe et au bloc opératoire ?

13. Do you know which elements would help you to master hysterectomy better? Connaissez-vous les éléments qui vous permettraient de mieux maîtriser l'hystérectomie ?

14. Can you cite a specific gesture of hysterectomy that you do not perfectly understand, and tell me what would help you to understanding it? What kind of information? With what material?
    Pouvez-vous me citer un geste d'hysterectomie que vous ne maîtrisez pas complètement, et me dire ce qui vous aiderait à le comprendre ? Quel genre d'information ? Sur quel(s) support(s) ? Pourquoi ?

Figure B.3: Interview before training

Appendix C

Interview after training with the video of hysterectomy

Post-Training Interview

Participant ID	
Interviewer	
Intern Year	
Hospital	

Your experience

1. Compared to how you felt before,. how far do you feel now from being able to perform a hysterectomy by yourself? Is this distance greater, unchanged, smaller ?
   Comparé au premier entretien, maintenant à quel point est-ce que vous vous sentez éloigné(e) de la capacité de réaliser une hystérectomie par vous-même ? Cette distance a-t-elle grandie, est-elle la même, plus petite ?

2. Has your comprehension of the procedure changed or is it the same? Votre compréhension de la procédure a-t-elle changé ou est-elle la même ?

3. Have you been training with other material than the video we have given you? Vous êtes vous entraîné(e)s avec autre chose que la vidéo que nous vous avons donné ? Si oui, pendant combien de temps et pourquoi ?

4. Can you tell me how many hysterectomies you have seen since last time? Have participated to ? With what role ?
   Pouvez-vous me dire combien d'hystérectomies vous avez vues depuis la dernière fois ? A combien d'hystérectomies vous avez participé ? Avec quel(s) rôle(s) ?

[Si aucune, passer à Your opinion on the video]

5. **If you have seen one or more hysterectomies**, do you remember one in particular? Why? **Si tu as vu une ou plusieurs hystérectomies depuis la dernière fois,** te souviens-tu d'une en particulier ? Pourquoi ?

6. How much of the procedure did you understand? A quel point avez-vous compris la procédure ?

7. Did you think of the video during this procedure? Avez-vous pensé à la vidéo pendant cette procédure ?

8. What moments made you think of the video? Why? Quels moments vous ont fait penser à la vidéo ? Pourquoi ?

9. Did the fact that you thought of the video help you? Le fait de penser à la vidéo vous a-t-il aidé(e) ? Pourquoi ? [Développer]

[Relancer..]

FIGURE C.1: Interview after training

Your opinion on the video

10. Can you tell me what you thought of the video? Why ?
    Pouvez-vous me dire ce que vous avez pensé de la vidéo ? Pourquoi ?

Differences between video and surgical education

11. Can you tell me what is different between what you saw the video and what you learnt during the course of your studies?
    Pouvez-vous me dire quelle(s) étai(en)t la/les différence(s) entre ce que vous avez vu dans la vidéo et ce que vous apprenez pendant votre cursus ? Si besoin préciser : par rapport aux livres, cours, bloc opératoire, autres vidéos qu'ils voient du bloc opératoire…

12. Do you consider these differences to be beneficial for learning? Ces différences vous semblent-elles bénéfiques pour l'apprentissage ?

You and the video

<u>[If they have seen no hysterectomy]</u>

13. Do you think that having this video would change your perceptions, next time you go to the Operating Room to perform (part of) a hysterectomy?
    Pouvez-vous me dire si oui ou non cette vidéo va changer vos perceptions, la prochaine fois que vous irez au bloc opératoire pour réaliser (partie d') une hystérectomie ?

14. What has changed in your mental representation and comprehension of the gestures performed by the expert after viewing the video?
    Qu'est-ce qui a changé dans votre représentation mentale et compréhension des gestes effectués par l'expert après avoir vu la vidéo ?

15. What has changed in your mental representation and comprehension of the steps of the procedure after viewing the video?
    Qu'est-ce qui a changé dans votre représentation mentale et compréhension étapes de la procédure après avoir vu la vidéo ?

16. Can you tell me what elements of the video will help you the most (if some elements will) ? Or some elements that you remember specifically?

Figure C.2: Interview after training

Pouvez-vous me dire quels éléments de la vidéo vous aideront le plus (si certains éléments vous aideront) ? Ou bien des éléments que vous avez spécifiquement retenu ?

Your suggestions

17. In your opinion, does this video lack information on hysterectomy or is it complete enough? A votre avis, cette vidéo manque-t-elle d'informations sur l'hystérectomie ou bien est-elle assez complète ?

18. What would you suggest to add?
Que suggéreriez-vous d'ajouter ?

19. What would you suggest to remove or change?
Que suggéreriez-vous d'enlever ou de changer ?

Figure C.3: Interview after training

Appendix D

Model of ceasarian section

Intervention Domains (Les différents cas de figure)	Steps (Les étapes)	Actor (Les acteurs)	Rules of action (Les régles d'action)	Operators (Les opérateurs ou actions qui "changent l'état du monde)	Controls (Les actions qui servent à vérifier avant d'agir ou après avoir agi)	Additional Information (Connaissances à maîtriser)
Age gestationnel, la pathologie obstétricale anté- ou per-partum, l'obésité maternelle, les antécédents chirurgicaux, la rupture des membranes, le début du travail, l'indication de la césarienne et son degré d'urgence, le type d'anesthésie, l'expérience du chirurgien, l'utilisation d'antibiotiques et le lieu d'exercice						
	Installation			Installez la patiente en décubitus dorsal, les jambes allongées, les bras à 90°, non attachés. Installez-la en proclive gauche 12,5°-15°		Les bras ne sont pas attachés pour éviter un sentiment de frustration de la maman de ne pouvoir libérer ses bras lorsqu'elle voit son bébé. La position en proclive gauche permet de réduire la compression aortico-cave
	Sondage vésical				Vérifiez que la patiente est sondée	
	Préparation de la peau			Réalisez le badigeonnage depuis les mamelons jusqu'au pubis en gardant les deux éipnes iliaques antérosupérieures libres	Vérifiez que les deux épines iliaques antérosupérieures sont libres	
	Incision cutanée			Réalisez une incision selon Cohen-Stark consistant à une incision transverale d'environ 13cm, 3cm au dessus du pubis	Vérifier l'indication de la césarienne: l'incision en dépend	Il existe aussi d'autres types d'incision: verticale, transversale avec ou sans ligature des vaisseaux épigastriques. Pour le choix de l'incision plusieurs critères rentrent en compte : l'esthétique (raison pour laquelle l'incision transversale a pris le pas sur l'incision verticale) le temps d'ouverture (moins long avec une ouverture de type Jöel-Cohen), la facilité d'extraction fœtale (importante pour ne pas transformer un accouchement par voie basse difficile en un accouchement par voie haute traumatique pour la mère et l'enfant) et le rsique de complications per- ou post- opératoires inhérentes à chaque type d'incision
	Incision de la graisse et de l'aponévrose			Dans la région médiane, incisez uniquement sur 3cm la graisse sus aponévrotique jsuqu'au plan de l'aponévrose des grands droits		
				Appliquez ce principe de la boutonnière à chacun des plans		
				Poussez les tissus sous-cutanés pour identifier le fascia sous-jacent	Identifiez le fascia sous-cutané	

Figure D.1: Model of C-Section

				Incisez l'aponévrose sur 1cm de part et d'autre de la ligne blanche de manière à pouvoir insérer deux doigts	Veillez à ne pas inciser les muscles grands droits	Position of the rectus maximus muscles
	Digitoclasie			Agrandissez l'ouverture de l'aponévrose latéralement par écartement digital sur toute la largeur de l'incision cutanée		
				Crochetez et ouvrez le péritoine pariétal au doigt: Ouvrez-le à environ 2cm au-dessous du niveau de sa fixation à l'utérus dans la ligne médiane		
				Etendez-le latéralement de chaque côté: le péritoine peut alors être saisi à l'aide de pinces et la vessie peut être séparée doucement du segment inférieur de façon brutale avec l'index		
		Operator, assistant		Ecartez de façon identique les muscles et le péritoine par les doigts de l'opérateur et de l'aide		Curvy lininear extension is essential because direct transverse extension often leads to inadvertent msucle incisions and bleeding
			Si vous vous trouvez en présence d'adhérences (en cas de césarienne antérieure par exemple)	Décollez le péritoine vésico-utérin	Vérifiez s'il y a des adhérences	
		Assistant		Exposez avec une valve sus-pubienne	Identifiez le segment inférieur, le cul-de-sac vésico utérin et la vessie qui réalise un renflement discret	Cette exposition permet de visualiser clairement le segement inférieur, le siège de l'hystérotomie
					Identifiez le péritoine utéro-vésical pour vérifier si adhérences et vessie pas remontée	Aucun décollement vésico-utérin n'est nécessaire
					Palpez l'utérus	L'utérus est palpé pour vérifier la présentation fœtale et l'alignement
	Hysterotomie		Si aucune difficulté n'est prévue à l'extraction fœtale	Incisez l'utérus horizontalement en monobloc sur le segment inférieur	Vérifiez que vous êtes au moins 2cm au dessus de la marge vésicale. Prenez garde de ne pas blesser une partie fœtale sous jacente	Une hytérotomie transversale est moins associé à un risuqe de rupture utérine ultérieure
				Réalisez une petite ouverture utérine centrale au bistouri		
			Si une difficulté est prévue à l'extraction fœtale (placenta accreta....)	Invisez verticalement l'utérus, sur le coprs utérin (hystérotomie corporéale)	Vérifiez si une difficulté est prévue à l'extraction fœtale	Ce type de césarienne impose le recours à des césariennes itératives, car ce type de cicatrice est plus fragile et risque une rupture utérine en cas d'accouchement ultérieur par les voies naturelles
			Si vous rencontrez une difficulté pendant l'extraction fœtale, suite à une incision transverse	Elargissez verticalement et crânialement la cicatrice		Cela permet d'avoir plus d'espace et de place pour manœuvrer. Cette cicatrice impose aussi le recours à des césariennes itératives

Figure D.2: Model of C-Section

				Elargissez l'incision utérine aux doigts par traction divergente des index selon un plan cranio-caudal		L'ouverture avec les doigts minimise les risques de lacération fœtale. Le plan cranio-caudal minimise les risques de saignement. Lors de l'églargissement latéral de l'hystérotomie, la complication la plus fréquente est une lésion des pédicules utérins
		Assistant.e		Aspirez le long de l'incision faite par l'opérateur		Cela permet de garder le champ propre et d'éviter de léser le fœtus
			Si le saignement est important	Tamponnez avec des compresses	Vérifiez le saignement	Cela permet une meilleure visualisation et réduit les risques de blessure
			Si vous observez des membranes amniotique, du fluide maniotique ou le fœtus, alors vous êtes dans l'utérus		Confirmez l'entrée dans l'utérus	L'entrée dans l'utérus est confirmée par la visualisation des membranes amniotiques, de fluide ou du fœtus
				Réalisez l'amniotomie		Il vaut mieux le faire avec doigts pour éviter les blessures fœtales
				Saisissez la présentation avec la main, fléchissez-la et remontez-la au niveau de l'hystérotomie, dans l'axe de dégagement		
					Pendant l'extraction, vérifiez que vous n'êtes pas en train d'exercer un effet levier sur le segment inférieur	
				Retirez la valve sus pubienne		
	Extraction		Si la présentation est céphalique	Réalisez le dégagement de la tête par efforts de poussée maternelle		Proscrivez le mouvement de levier de la main endo-utérine pour éviter d'éventuelles lésions (vésicales, cervicales, aux pédicules utérins)
		Assitant.e	Si l'extraction fœtale est compliquée	Appliquez une pression abdominale sur le fond utérin		
			Si les mains ne suffisent pas à faire sortir le fœtus	Recourez à une extraction par forceps ou par ventouse		
			Si la tête est très haute par rapport à l'incision et que l'expression fundique ne suffit pas à l'amener au niveau de l'hystérotomie (présentation transverse)	Effectuez une version par manouvre interne et grande extraction du siège	Vérifiez la position de la tête	
				Faites son application au plus près de l'occupit pour favorisze au maximum la fliexion de la tête et la tracter vers l'ouverture utérine toujours en maintenant l'expression fundique		
			Si la présentation est en siège	L'extraction peut être quasi spontanée grâce à l'expression fundique		
			S'il surgit une difficulté	Des tractions inguinales sont suffisantes pour dégager un siège décomplété, ainsi que l'abaissement des deux pieds pour un siège complet		

Figure D.3: Model of C-Section

				Clampez le cordon ombilical 30 secondes à 1 minute après l'extraction		Cela améliore l'hémodynamique fœtale
				Coupez le cordon entre deux pinces		
				Réalisez les prélévements		
	Délivrance			Il est recommandé de réaliser une délivrance dirigée par injection immédiate d'un utérotonique.		Cela permet de réduire le risque d'endométrite postopératoire et les pertes sanguines
					Si les saignements sont d'emblée importants sans décollement du placenta, une délivrance artificielle est réalisée	
		Assistant.e		Aspirez le sang et le fluide amniotique		
					Effectuez systématiquement un examen de l'utérus	
				Idéalement n'extériorisez pas l'utérus		Cela diminue le risque hémorragique
	Hysteroraphie			Exposez le segment inférieur à l'aide d'une pince en cœur		
				Démarrez la suture à l'angle homolatéral à l'opérateur à l'aide d'un fil à résorption lente de type Vicryl 1		
				Réalisez un point en X, en veillant à placer le nœud à l'extérieur de l'angle	Visualisez totalement le champ opératoire	Aucun point ne doit être effectué à l'aveugle afin d'éviter tout lésion à l'artère utérine ou à l'uretère
				Procédez de la même manière à l'autre angle		
				Pratiquez la suture utérine en 1 plan par un surjet simple		
		Assistant.e	Si vous êtes dans l'axe de la suture alors il existe moins de risques de déchirer le tissu myométrial	Maintenez la traction du surjet	Veillez à rester dans l'axe de la suture	
				Chaque point est réalisé avec un espacement régulier		It avoids tearing the myometrial tissue
	Contrôle hémosthase				Vérifiez l'hémostase	
				Vérifiez les plaies vésicales: test au bleu si doute	Suture par points simples de Vycril 3.0	
			Si hémarogie de la délivrance		Visuel	500ml pertes sanguines
				utérotonique type nalador		
				technique de ballonet intra utérin		
				ligature vasculaire: triple ligature de tsirulnikov, ligature des artères hippograstriques, hystérectomie d'hémostase		
				Completez si besoin avec de nouveaux points		Points en U de rapprochement des berges ou point en X hémostatique
				si doute lésion uretère	urétérolise	
					Inspectez la cavité abdominale	
				Effectuez une toilette péritonéale		L'objectif de la toilette est de retirer les caillots, le liquide étant résorbé par le péritoine
						Le péritoine péritonéal n'est pas suturé

Figure D.4: Model of C-Section

				Faites le compte des compresses		
					Vérifiez les annexes	
	Fermeture aponévrotique			Refermez l'aponévrose des muscles grands droits est refermée par un surjet de Vicryl 1		
				De la même manière que précédemment, l'opérateur effectue un premier point d'arrêt du côté homolatéral	Veillez à bien prendre les 2 feuillets de l'aaponévrose des muscles grands droits	
		Assistant.e		Veillez à appliquer une traction constante dans l'axe du surjet		
			Si la paroi adipeuse fait plus de 3cm (en cas de patiente obèse), alors il est possible de suturer le fascia superficialis		Vérifiez la paroi adipeuse	Cela limite le risque de désunion
	Fermeture cutanée			Fermez la peau par un surjet intradermique, par des points séparés ou des agraphes		
				Appliquez un pansement simple		Un pansement compressif est contre-indiqué et expose à un risque d'hémorragie du post partum par rétention vésicale
				Effectuez la surveillance post opératoire pendant 2 heures		

FIGURE D.5: Model of C-Section

Appendix E

MCQ for ceasarian section

ETUDE REVAP

Questionnaire d'évaluation : Césarienne

Anatomie :

Concernant l'incision cutanée selon Joel-Cohen :

A- Incision médiane sous ombilicale
B- Incision transversale arciforme
C- Incision transversale rectiligne
D- 3 cm au-dessus de la symphyse pubienne
E- 3 cm sous l'ombilic

CD

Concernant l'hystérotomie :

A- Elle est réalisée au niveau du corps utérin transversalement
B- Elle est réalisée au niveau du segment inférieur longitudinalement
C- Elle est réalisée au niveau du corps utérin transversalement
D- Elle est réalisée au niveau segment inférieur transversalement
E- Elle est réalisée au niveau cervical transversalement

D

Concernant le segment inférieur :

A- Il se développe majoritairement au 3eme trimestre de la grossesse
B- Il est présent à 28 SA chez une primipare
C- Son développement est plus tardif chez les multipares
D- Le péritoine viscéral est facilement développable à son niveau
E- Il est principalement vascularisé par le ligament rond

ABCD

Quelle est la complication possible la plus fréquente lors de l'élargissement latéral de l'hystérotomie?

A- Lésions des pédicules utérin
B- Lésion urétérale
C- Lésion de l'artère ombilicale
D- Lésion sigmoïdienne
E- Lésion vésicale

A

Quelle structure est particulièrement à risque lors du contrôle d'un saignement de la branche ascendante de l'artère utérine ?

A- Uretère
B- Ligament suspenseur de l'ovaire

Figure E.1: MCQ for C-Section

C- Rectum
D- Artère ombilicale
E- Artère iliaque externe

A

Quelles particularités anatomiques liées à la grossesse nécessitent un contrôle précis de la zone d'hystérotomie ?

A- Dextrorotation de l'utérus
B- Développement d'un segment inférieur
C- Présence d'une « linea nigra »
D- Antéversion utérine
E- Présence de fibrome utérin

AB

Concernant le segment inférieur de l'utérus, quelles sont les affirmations vraies ?

A - le segment inférieur est présent au niveau de la portion inférieure de l'isthme utérin, au contact du relief cervical sur un utérus non gravide

B - le segment inférieur se constitue progressivement dès le début de la grossesse

C - la couche musculaire profonde est constituée de fibres transversales

D - le réseau veineux a une disposition transversale

E - la digitoclasie « atraumatique » de l'hystérotomie doit se faire dans un sens craniocaudal

CDE

Concernant l'incision abdominale, quelles sont les affirmations exactes ?

A - il s'agit fréquemment d'une incision médiane sous-ombilicale

B - elle peut s'effectuer sur la même cicatrice qu'une précédente césarienne

C - elle peut s'effectuer sur la même cicatrice qu'une précédente intervention

D - la fermeture cutanée nécessite généralement la mise en place d'un Redon

E - la fermeture cutanée peut s'effectuer par un surjet intradermique

BCE

Concernant l'hystérotomie, quelles sont les affirmations exactes ?

A - elle s'effectue généralement sur le corps utérin

B - elle est généralement transversale

C - elle peut être longitudinale

D - il s'agit de la seule zone intrapéritonéale lors de la césarienne extrapéritonéale

Figure E.2: MCQ for C-Section

E - elle est facilitée par un segment inférieur non amplié

BC

Instrumentation :

Quel est (sont) le(s) instrument(s) indispensable(s) permettant d'effectuer tout les temps opératoire jusqu'à l'extraction fœtale en cas d'extrême urgence selon Joel Cohen ?

A- Valve sus-pubienne
B- Pince de Kocher
C- Bistouri froid
D- Pince de Jean-Louis Faure
E- Ecarteurs de Faraboeuf

C

Quel type de fil est utilisé pour la fermeture de l'hystérotomie ?

A- Fil tressé à résorption lente type Vicryl 1
B- Fil tressé à résorption rapide Vicryl rapide 1
C- Fil tressé à résorption lente type Vicryl 2-0
D- Fil tressé à rapide Vicryl rapide 2-0
E- Monofilament à résorption rapide type Monocryl 2-0

A

Quelles pinces sont les plus appropriés afin d'exposer le segment inférieur lors de l'hystérographie?

A- Pince Duval
B- Pince en cœur
C- Pince Kocher
D- Pince Kelly
E- Pince Jean-Louis Faure

AB

Quel type de point est le plus hémostatiques en cas de saignement de l'hystérorraphie ?

A- Point en U
B- Point en X
C- Point de Blair-Donati
D- Point simple
E- Point inversant

B

Technique chirurgicale :

Quel élément de l'installation permet de réduire la compression aortico-cave ?

A- Rotation latérale droite de 12,5 à 15°
B- Rotation latérale gauche de 12,5 à 15 °
C- Position de Trendelenburg
D- Bras à 90°
E- Position déclive

Figure E.3: MCQ for C-Section

B

Lors d'une césarienne selon Joel-Cohen comment est réalisée l'ouverture et l'écartement aponévrotique?

A- Digitoclasie par traction divergente
B- Décollement musculo-aponévrotique aux ciseaux de Mayo
C- Moucheture au bistouri froid de part et d'autre de la ligne blanche
D- Décollement musculo-aponévrotique au bistouri électrique
E- Section au bistouri électrique

AC

Quel geste chirurgical peut être nécessaire avant l'hystérotomie en cas de césarienne antérieure?

A- Décollement vésico-utérin
B- Incision corporéale
C- Extériorisation de l'utérus
D- Incision médiane sous-ombilicale
E- Incision de Mouchel

A

Quel geste semble minimiser le risque de plaie d'organe lors de l'ouverture du péritoine pariétal?

A- Ouverture péritonéal aux ciseaux
B- Ouverture entre 2 pince de Kocher
C- Ouverture péritonéale aux doigts
D- Ouverture au bistouri électrique
E- Refoulement des anses digestives

C

Quel type d'hystérotomie est le moins associée à un risque de rupture utérine ultérieure?

A- Hystérotomie segmentaire transversale
B- Hystérotomie corporéale transversale
C- Hystérotomie segmentaire longitudinale
D- Hystérotomie en « T »
E- Hystérotomie fundique transversale

A

Combien de plans sont nécessaires à une bonne solidité de l'hystérorraphie ?

A- 1
B- 2
C- 3
D- 4
E- 5

1

Concernant l'extraction fœtale en position céphalique : quels gestes doivent être réalisés?

Figure E.4: MCQ for C-Section

A- Protection vésicale à l'aide d'une valve sus-pubienne
B- Pression du fond utérin par l'aide, avant tout geste intra-utérin
C- Rotation de la tête en présentation de la face
D- Leger refoulement du mobile fœtal jusqu'à l'hystérotomie
E- Injection de PABAL permettant une meilleure contractilité utérine

D

<u>Quel mouvement est à proscrire afin d'éviter d'éventuelle lésions (vésicales, cervicale, pedicules utérins) lors de l'extraction?</u>

A- Mouvement de levier de la main endo-utérine
B- Leger refoulement du mobile fœtale jusqu'à l'hystérotomie
C- Protection vésicale à l'aide d'une valve sus-pubienne durant l'extraction
D- Pression du fond utérin par l'aide
E- Aspiration du liquide amniotique

AC

<u>Quel geste doit être effectué avant de débuter de l'hysterorraphie ?</u>

A- Révision utérine
B- Vérification des annexes
C- Toilette des gouttières pariéto-coliques
D- Comptes des champs
E- Extériorisation de l'utérus

A

<u>Dans la technique de Joel Cohen:</u>

A – Le décollement musculo-aponévrotique est réalisé aux ciseaux

B - l'ouverture pariétale consiste en une incision rectiligne à environ 3 cm au-dessous de la ligne interiliaque

C - l'hystérotomie est corporéale

D - l'hystérotomie est suturée en un plan

E - seul le péritoine pariétal est suturé par un surjet simple

D

Figure E.5: MCQ for C-Section

Echelle de notation globale de la performance opératoire

Merci d'entourer le numéro correspondant à la performance pour chaque catégorie, peu importe le niveau d'entraînement

Respect des tissus :				
1	2	3	4	5
Manipulation inappropriée des tissus ou traumatismes tissulaires		Manipulation précautionneuse des tissus mais occasionnellement des traumatismes sont causés par inadvertance		Manipulation appropriée constante des tissus avec des traumatismes minimaux
Temps et mouvements :				
1	2	3	4	5
Réalisation de mouvements non nécessaires		Efficacité du rapport temps/mouvements mais quelques mouvements non nécessaires		Nette économie de mouvement et efficacité maximale
Manipulation des instruments :				
1	2	3	4	5
Utilisation inappropriée des instruments ou gestes maladroits		Utilisation appropriée des instruments mais parfois raideur ou maladresse		Mouvements fluides avec les instruments et aucune maladresse
Connaissance des instruments :				
1	2	3	4	5
Demande ou utilisation fréquente du mauvais instrument		Connaissance du nom de la plupart des instruments et utilisation appropriée des instruments		Connaissance manifeste du nom et de la fonction des instruments
Déroulé de l'intervention :				
1	2	3	4	5
Arrêt fréquent de l'intervention et incertitude quant au prochain geste		Démonstration d'anticipation et progression raisonnable de la procédure		Anticipation manifeste du cours de l'intervention avec une continuité sans effort entre les gestes
Connaissance spécifique de la procédure :				
1	2	3	4	5
Connaissance déficiente. Besoin d'instructions spécifiques durant la plupart des étapes		Connaissance de toutes les étapes importantes de l'intervention		Familiarité avec tous les aspects de l'intervention

FIGURE E.6: OSATS Score

Bibliography

[tec] Definition of techno-pedagogy. https://ccerbal.uottawa.ca/ltirg/techno-pedagogy. Accessed: 2019-11-04. *Cited page 68*

[2] Abaza, R. (2009). The robotic surgery era and the role of laparoscopy training. *Therapeutic advances in urology*, 1(3):161–165. *Cited page 18*

[3] Abe, T., Raison, N., Shinohara, N., Khan, M. S., Ahmed, K., and Dasgupta, P. (2018). The effect of visual-spatial ability on the learning of robot-assisted surgical skills. *Journal of surgical education*, 75(2):458–464. *Cited page 21*

[4] Ahlering, T. E., Skarecky, D., Lee, D., and Clayman, R. V. (2003). Successful transfer of open surgical skills to a laparoscopic environment using a robotic interface: initial experience with laparoscopic radical prostatectomy. *The Journal of urology*, 170(5):1738–1741. *2 citations page 10 and 14*

[5] Ahmet, A., Gamze, K., Rustem, M., and Sezen, K. A. (2018). Is video-based education an effective method in surgical education? a systematic review. *Journal of surgical education*, 75(5):1150–1158. *2 citations page 9 and 40*

[6] Aleem, I. S., Vidal, M., and Chapeskie, J. (2018). Systems, devices, and methods for laser eye tracking. US Patent 9,904,051. *Cited page 18*

[7] Angell, J., Gomez, M. S., Baig, M. M., and Abaza, R. (2013). Contribution of laparoscopic training to robotic proficiency. *Journal of endourology*, 27(8):1027–1031. *Cited page 18*

[8] Antiel, R. M., Thompson, S. M., Hafferty, F. W., James, K. M., Tilburt, J. C., Bannon, M. P., Fischer, P. R., Farley, D. R., and Reed, D. A. (2011). Duty hour recommendations and implications for meeting the acgme core competencies: views of residency directors. In *Mayo Clinic Proceedings*, volume 86, pages 185–191. Elsevier. *Cited page 10*

[9] Ashraf, H., Sodergren, M. H., Merali, N., Mylonas, G., Singh, H., and Darzi, A. (2018). Eye-tracking technology in medical education: A systematic review. *Medical teacher*, 40(1):62–69. *Cited page 18*

[10] Atkinson, P. and Silverman, D. (1997). Kundera's immortality: The interview society and the invention of the self. *Qualitative inquiry*, 3(3):304–325. *Cited page 43*

[11] Augestad, K. M., Butt, K., Ignjatovic, D., Keller, D. S., and Kiran, R. (2020). Video-based coaching in surgical education: a systematic review and meta-analysis. *Surgical endoscopy*, 34(2):521–535. *Cited page 9*

[12] Avellino, I., Bailly, G., Canlorbe, G., Belghiti, J., Morel, G., and Vitrani, M.-A. (2019). Impacts of telemanipulation in robotic assisted surgery. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019)*. *4 citations page vii, 14, 19, and 44*

[13] Balacheff, N. (1995). Conception, connaissance et concept. In *Séminaire de l'équipe DidaTech, IMAG*, pages 219–244. IMAG Grenoble. *Cited page 45*

[14] Balacheff, N. (2011). ck¢, un modèle pour relier connaissance et preuve en didactique des mathématiques. *Cited page 74*

[15] Balacheff, N. and Margolinas, C. (2003). ck¢ modèle de connaissances pour le calcul de situations didactiques. In *XII° école d'été de didactique des mathématiques*, pages 1–32. La Pensée Sauvage éditions. *3 citations page 42, 74, and 77*

[16] Barone, J. E., Tucker, J. B., and Bull, S. M. (2003). The leapfrog initiative: a potential threat to surgical education. *Current surgery*, 60(2):218–221. *2 citations page 10 and 73*

[17] Basteris, A., Bracco, L., and Sanguineti, V. (2012). Robot-assisted intermanual transfer of handwriting skills. *Human movement science*, 31(5):1175–1190. *Cited page 5*

[18] Berman, L., Rosenthal, M. S., Curry, L. A., Evans, L. V., and Gusberg, R. J. (2008). Attracting surgical clerks to surgical careers: role models, mentoring, and engagement in the operating room. *Journal of the American College of Surgeons*, 207(6):793–800. *Cited page 2*

[19] Blavier, A., Gaudissart, Q., Cadière, G.-B., and Nyssen, A.-S. (2007a). Comparison of learning curves and skill transfer between classical and robotic laparoscopy according to the viewing conditions: implications for training. *The American journal of surgery*, 194(1):115–121. *5 citations page 10, 17, 19, 20, and 36*

[20] Blavier, A., Gaudissart, Q., Cadiere, G.-B., and Nyssen, A.-S. (2007b). Perceptual and instrumental impacts of robotic laparoscopy on surgical performance. *Surgical endoscopy*, 21(10):1875–1882. *5 citations page 10, 17, 19, 21, and 36*

[21] Bril, B. (2002). Apprentissage et contexte. *Intellectica*, 35(2):251–268. *Cited page 88*

[22] Chalard, R., Reversat, D., Morel, G., Mozer, P., and Vitrani, M.-A. (2018). Precisely positioning the tip of an instrument inserted through an orifice with a free wrist robot: application to prostate biopsies. *International journal of computer assisted radiology and surgery*, 13(5):611–618. *Cited page 16*

[23] Cheatle, A., Pelikan, H., Jung, M., and Jackson, S. (2019). Sensing (co) operations: Articulation and compensation in the robotic operating room. *Proceedings of the ACM on Human-Computer Interaction*, 3(CSCW):1–26. *2 citations page 19 and 44*

[24] Chenkin, J., Lee, S., Huynh, T., and Bandiera, G. (2008). Procedures can be learned on the web: a randomized study of ultrasound-guided vascular access training. *Academic Emergency Medicine*, 15(10):949–954. *Cited page 3*

[25] Choi, A.-R. A., Tamblyn, R., and Stringer, M. D. (2008). Electronic resources for surgical anatomy. *ANZ journal of surgery*, 78(12):1082–1091. *Cited page 3*

[26] Clarke-Pearson, D. L. and Geller, E. J. (2013). Complications of hysterectomy. *Obstetrics & Gynecology*, 121(3):654–673. *Cited page 48*

[27] Corrigan, M., Reardon, M., Shields, C., and Redmond, H. (2008). "surgent"—student e-learning for reality: the application of interactive visual images to problem-based learning in undergraduate surgery. *Journal of surgical education*, 65(2):120–125. *2 citations page 3 and 40*

[28] Criley, J. M., Keiner, J., Boker, J. R., Criley, S. R., and Warde, C. M. (2008). Innovative web-based multimedia curriculum improves cardiac examination competency of residents. *Journal of Hospital Medicine: An Official Publication of the Society of Hospital Medicine*, 3(2):124–133. *Cited page 3*

[29] Cuschieri, A. (2006). Nature of human error: implications for surgical practice. *Annals of surgery*, 244(5):642. *Cited page 1*

[30] DaRosa, D. A., Bell Jr, R. H., and Dunnington, G. L. (2003). Residency program models, implications, and evaluation: results of a think tank consortium on resident work hours. *Surgery*, 133(1):13–23. *2 citations page 10 and 73*

[31] De Clercq, P., Kaiser, K., and Hasman, A. (2008). Computer-interpretable guideline formalisms. *Studies in health technology and informatics*, 139:22. *Cited page 42*

[32] De Witte, B., Di Rienzo, F., Martin, X., Haixia, Y., Collet, C., and Hoyek, N. (2018). Implementing cognitive training into a surgical skill course: a pilot study on laparoscopic suturing and knot tying. *Surgical innovation*, 25(6):625–635. *Cited page 21*

[33] Debas, H. T. (2002). Surgery: a noble profession in a changing world. *Annals of surgery*, 236(3):263. *Cited page 1*

[34] Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, F., Goldman, R., Hall, R., Koschmann, T., Lemke, J. L., Sherin, M. G., et al. (2010). Conducting video research in the learning sciences: Guidance on selection, analysis, technology, and ethics. *The journal of the learning sciences*, 19(1):3–53. *Cited page 40*

[35] Despinoy, F., Zemiti, N., Forestier, G., Sánchez, A., Jannin, P., and Poignet, P. (2018). Evaluation of contactless human–machine interface for robotic surgical training. *International journal of computer assisted radiology and surgery*, 13(1):13–24. *Cited page 17*

[36] Dharia, S. and Falcone, T. (2005). Robotics in reproductive medicine. fertility and sterility. *Cited page 15*

[37] DiMaio, S., Hanuschik, M., and Kreaden, U. (2011). The da vinci surgical system. In *Surgical Robotics*, pages 199–217. Springer. *Cited page 6*

[38] Dong, L. (2017). *Assistance to laparoscopic surgery through comanipulation*. PhD thesis, Paris 6. *2 citations page 20 and 24*

[39] Dunning, K., Liedtke, E., Toedter, L., and Rohatgi, C. (2008). Outpatient surgery centers draw cases away from hospitals, impact resident training volume. *Journal of surgical education*, 65(6):460–464. *2 citations page 10 and 73*

[40] Dunnington, G. L. (1996). The art of mentoring. *The American journal of surgery*, 171(6):604–607. *Cited page 3*

[41] Ellis, C. and Patti, C. (2014). With heart: Compassionate interviewing and storytelling with holocaust survivors. *Storytelling, Self, Society*, 10(1):93–118. *Cited page 43*

[42] Emken, J. L., Benitez, R., and Reinkensmeyer, D. J. (2007). Human-robot cooperative movement training: learning a novel sensory motor transformation during walking with robotic assistance-as-needed. *Journal of neuroengineering and rehabilitation*, 4(1):8. *Cited page 6*

[43] Erden, M. S. and Marić, B. (2011). Assisting manual welding with robot. *Robotics and Computer-Integrated Manufacturing*, 27(4):818–828. *Cited page 21*

[44] Faure, J.-L. (1920). *L'âme du chirurgien*, volume 8. G. Crés et Cie. *Cited page 91*

[45] Ferrand-Sorbets, S., Taussig, D., Fohlen, M., Bulteau, C., Dorfmuller, G., and Delalande, O. (2010). Frameless stereotactic robot-guided placement of depth electrodes for stereo-electroencephalography in the presurgical evaluation

of children with drug-resistant focal epilepsy. In *CNS Annual Meeting*. CNS Annual Meeting. *Cited page 16*

[46] Ferzli, G., Timoney, M., Nazir, S., Swedler, D., and Fingerhut, A. (2015). Importance of the node of calot in gallbladder neck dissection: an important landmark in the standardized approach to the laparoscopic cholecystectomy. *Journal of Laparoendoscopic Advanced Surgical Techniques*, 25(1):28–32. *2 citations page vii and 24*

[47] Fosnot, C. T. and Perry, R. S. (1996). Constructivism: A psychological theory of learning. *Constructivism: Theory, perspectives, and practice*, 2(1):8–33. *3 citations page 46, 74, and 77*

[48] Franzese, C. B. and Stringer, S. P. (2007). The evolution of surgical training: perspectives on educational models from the past to the future. *Otolaryngologic Clinics of North America*, 40(6):1227–1235. *Cited page 3*

[49] Fukuta, J., Gill, N., Rooney, R., Coombs, A., and Murphy, D. (2020). Use of 360° video for a virtual operating theatre orientation for medical students. *Journal of surgical education*. *Cited page 9*

[50] Gallagher, A. G., Richie, K., McClure, N., and McGuigan, J. (2001). Objective psychomotor skills assessment of experienced, junior, and novice laparoscopists with virtual reality. *World journal of surgery*, 25(11):1478–1483. *Cited page 17*

[51] Gawande, A. A., Thomas, E. J., Zinner, M. J., and Brennan, T. A. (1999). The incidence and nature of surgical adverse events in colorado and utah in 1992. *Surgery*, 126(1):66–75. *Cited page 1*

[52] Glaser, R. (1984). Education and thinking: The role of knowledge. *American psychologist*, 39(2):93. *Cited page 68*

[53] Goldman, R., Pea, R., Barron, B., and Derry, S. J. (2014). *Video research in the learning sciences*. Routledge. *Cited page 40*

[54] Gomes, P. (2011). Surgical robotics: Reviewing the past, analysing the present, imagining the future. *Robotics and Computer-Integrated Manufacturing*, 27(2):261–266. *Cited page 6*

[55] Graham, G. (2000). Behaviorism. *Cited page 46*

[56] Green, J. L., Suresh, V., Bittar, P., Ledbetter, L., Mithani, S. K., and Allori, A. (2019). The utilization of video technology in surgical education: a systematic review. *Journal of Surgical Research*, 235:171–180. *Cited page 9*

[57] Gruijthuijsen, C., Colchester, R., Devreker, A., Javaux, A., Maneas, E., Noimark, S., Xia, W., Stoyanov, D., Reynaerts, D., Deprest, J., et al. (2018). Haptic guidance based on all-optical ultrasound distance sensing for

safer minimally invasive fetal surgery. *Journal of medical robotics research*, 3(03n04):1841001. *2 citations page vii and 15*

[58] Guadagnoli, M. A. and Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of motor behavior*, 36(2):212–224. *Cited page 6*

[59] Gubrium, J. F. and Holstein, J. A. (2002). From the individual interview to the interview society. *Handbook of interview research: Context and method*, pages 3–32. *Cited page 43*

[60] Gurusamy, K. S., Aggarwal, R., Palanivelu, L., and Davidson, B. R. (2009). Virtual reality training for surgical trainees in laparoscopic surgery. *Cochrane database of systematic reviews*, (1). *2 citations page 73 and 89*

[61] Hart, S. G. and Staveland, L. E. (1988). Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in psychology*, volume 52, pages 139–183. Elsevier. *Cited page 22*

[62] Harvey, A., Vickers, J. N., Snelgrove, R., Scott, M. F., and Morrison, S. (2014). Expert surgeon's quiet eye and slowing down: expertise differences in performance and quiet eye duration during identification and dissection of the recurrent laryngeal nerve. *The American Journal of Surgery*, 207(2):187–193. *3 citations page 18, 21, and 25*

[63] Hegarty, M. (2004). Dynamic visualizations and learning: Getting to the difficult questions. *Learning and Instruction*, 14(3):343–351. *Cited page 9*

[64] Helms, E., Schraft, R. D., and Hagele, M. (2002). rob@ work: Robot assistant in industrial environments. In *Proceedings. 11th IEEE International Workshop on Robot and Human Interactive Communication*, pages 399–404. IEEE. *Cited page 16*

[65] Herman, B., Zahraee, A. H., Szewczyk, J., Morel, G., Bourdin, C., Vercher, J.-L., and Gayet, B. (2011). Ergonomic and gesture performance of robotized instruments for laparoscopic surgery. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1333–1338. IEEE. *Cited page 17*

[66] Hermens, F., Flin, R., Ahmed, I., et al. (2013). Eye movements in surgery: A literature review. *Journal of Eye movement research*, 6(4):1–11. *Cited page 18*

[67] Heuer, H. and Luettgen, J. (2015). Robot assistance of motor learning: A neuro-cognitive perspective. *Neuroscience & Biobehavioral Reviews*, 56:222–240. *2 citations page 5 and 19*

[68] Hopper, A., Jamison, M., and Lewis, W. (2007). Learning curves in surgical practice. *Postgraduate medical journal*, 83(986):777–779. *Cited page 2*

[69] Huard, V. (2010). L'intérêt de la didactique professionnelle pour la mise en œuvre d'une pragmatique de formation. *Savoirs*, (2):73–94. *Cited page 58*

[70] Huber, T., Paschold, M., Hansen, C., Lang, H., and Kneist, W. (2018). Artificial versus video-based immersive virtual surroundings: analysis of performance and user's preference. *Surgical innovation*, 25(3):280–285. *3 citations page 8, 73, and 87*

[71] Huber, T., Paschold, M., Hansen, C., Wunderling, T., Lang, H., and Kneist, W. (2017). New dimensions in surgical training: immersive virtual reality laparoscopic simulation exhilarates surgical staff. *Surgical endoscopy*, 31(11):4472–4477. *3 citations page 8, 73, and 87*

[72] Huckman, R. S. and Pisano, G. P. (2006). The firm specificity of individual performance: Evidence from cardiac surgery. *Management Science*, 52(4):473–488. *Cited page 3*

[73] Hughes, G., Vadera, S., Bulacio, J., and Gonzalez-Martinez, J. (2013). Robotic placement of intracranial depth electrodes for long-term monitoring: Utility and efficacy. *Cleveland Clinic*. *Cited page 16*

[74] Issa, N., Schuller, M., Santacaterina, S., Shapiro, M., Wang, E., Mayer, R. E., and DaRosa, D. A. (2011). Applying multimedia design principles enhances learning in medical education. *Medical education*, 45(8):818–826. *Cited page 9*

[75] Jakopec, M., y Baena, F. R., Harris, S. J., Gomes, P., Cobb, J., and Davies, B. L. (2003). The hands-on orthopaedic robot" acrobot": Early clinical trials of total knee replacement surgery. *IEEE Transactions on Robotics and Automation*, 19(5):902–911. *Cited page 16*

[76] Kable, A., Gibberd, R., and Spigelman, A. (2002). Adverse events in surgical patients in australia. *International Journal for Quality in Health Care*, 14(4):269–276. *Cited page 1*

[77] Kirk, R. (1996). Teaching the craft of operative surgery. *Annals of the Royal College of Surgeons of England*, 78(1 Suppl):25–28. *2 citations page 41 and 78*

[78] Knight, S., Aggarwal, R., Agostini, A., Loundou, A., Berdah, S., and Crochet, P. (2018). Development of an objective assessment tool for total laparoscopic hysterectomy: a delphi method among experts and evaluation on a virtual reality simulator. *PloS one*, 13(1). *Cited page 48*

[79] Koehler, M. J., Mishra, P., Kereluik, K., Shin, T. S., and Graham, C. R. (2014). The technological pedagogical content knowledge framework. In *Handbook of research on educational communications and technology*, pages 101–111. Springer. *Cited page 68*

[80] Kondo, W., Zomer, M. T., Charles, L., Bourdel, N., Mage, G., and Canis, M. (2011). Total laparoscopic hysterectomy: surgical technique and results. *Advanced Gynecologic Endoscopy*, pages 263–292. *Cited page 48*

[81] Kopta, J. A. (1971). An approach to the evaluation of operative skills. *Surgery*, 70(2):297–303. *Cited page 41*

[82] Kotsis, S. V. and Chung, K. C. (2013). Application of see one, do one, teach one concept in surgical training. *Plastic and reconstructive surgery*, 131(5):1194. *2 citations page 3 and 73*

[83] Kümmel, J., Kramer, A., and Gruber, M. (2014). Robotic guidance induces long-lasting changes in the movement pattern of a novel sport-specific motor task. *Human movement science*, 38:23–33. *Cited page 5*

[84] Kyaw, B. M., Saxena, N., Posadzki, P., Vseteckova, J., Nikolaou, C. K., George, P. P., Divakar, U., Masiello, I., Kononowicz, A. A., Zary, N., et al. (2019). Virtual reality for health professions education: systematic review and meta-analysis by the digital health education collaboration. *Journal of medical Internet research*, 21(1):e12959. *2 citations page 73 and 89*

[85] Lalys, F. and Jannin, P. (2014). Surgical process modelling: a review. *International journal of computer assisted radiology and surgery*, 9(3):495–511. *Cited page 42*

[86] Land, M. and Tatler, B. (2009). *Looking and acting: vision and eye movements in natural behaviour*. Oxford University Press. *Cited page 21*

[87] Law, B., Atkins, M. S., Kirkpatrick, A. E., and Lomax, A. J. (2004). Eye gaze patterns differentiate novice and experts in a virtual laparoscopic surgery training environment. In *Proceedings of the 2004 symposium on Eye tracking research & applications*, pages 41–48. ACM. *3 citations page 18, 21, and 25*

[88] Leinhardt, G. and Greeno, J. G. (1986). The cognitive skill of teaching. *Journal of educational psychology*, 78(2):75. *Cited page 68*

[89] Lin Dong, G. M. (2021). Control strategy at different instrument points using lever model in laparoscopic surgery. *Accepted:IEEE ICARM 2021*. *Cited page 24*

[90] Logishetty, K., Gofton, W. T., Rudran, B., Beaulé, P. E., and Cobb, J. P. (2020). Fully immersive virtual reality for total hip arthroplasty: objective measurement of skills and transfer of visuospatial performance after a competency-based simulation curriculum. *JBJS*, 102(6):e27. *Cited page 8*

[91] Logishetty, K., Rudran, B., and Cobb, J. P. (2019a). Virtual reality training improves trainee performance in total hip arthroplasty: a randomized controlled trial. *The bone & joint journal*, 101(12):1585–1592. *Cited page 8*

[92] Logishetty, K., Western, L., Morgan, R., Iranpour, F., Cobb, J. P., and Auvinet, E. (2019b). Can an augmented reality headset improve accuracy of acetabular cup orientation in simulated tha? a randomized trial. *Clinical orthopaedics and related research*, 477(5):1190. *Cited page 8*

[93] Luengo, V., Larcher, A., and Tonetti, J. (2011). Design and implementation of a visual and haptic simulator in a platform for a tel system in percutaneuos orthopedic surgery. In *Medicine Meets Virtual Reality 18*, pages 324–328. IOS Press. *3 citations page 42, 47, and 67*

[94] Luengo, V., Troccaz, J., Dubois, M., and Jéromê, T. (2010). Teleos technology enhanced learning environment for orthopaedic surgery. *Cited page 6*

[95] Luengo, V., Vadcard, L., Dubois, M., and Mufti-Alchawafa, D. (2006). Teleos: de l'analyse de l'activité professionnelle à la formalisation des connaissances pour un environnement d'apprentissage. In *Actes d'IC*, pages 101–110. *3 citations page 42, 47, and 67*

[96] Luursema, J.-M., Verwey, W. B., and Burie, R. (2012). Visuospatial ability factors and performance variables in laparoscopic simulator training. *Learning and individual differences*, 22(5):632–638. *Cited page 21*

[97] MacKenzie, L., Ibbotson, J., Cao, C., and Lomax, A. (2001). Hierarchical decomposition of laparoscopic surgery: a human factors approach to investigating the operating room environment. *Minimally Invasive Therapy & Allied Technologies*, 10(3):121–127. *Cited page 42*

[98] Mago, J., Aricò, M., Da Silva, J., and Morel, G. (2019). Safe teleoperation of a laparoscope holder with dynamic precision but low stiffness. In *2019 International Conference on Robotics and Automation (ICRA)*, pages 2693–2699. IEEE. *Cited page 24*

[99] Mameli, A., Luengo, V., Cau, J., and Mesas, A. (2009). Méthodologie de conception d'un simulateur vidéo laparoscopique. de l'analyse des connaissances á la création des parcours d'apprentissage: Le cas de la chirurgie aortique. In *Actes de la conférence EIAH 2009*, pages 8–pages. *4 citations page 40, 44, 78, and 88*

[100] Marchal-Crespo, L., van Raai, M., Rauter, G., Wolf, P., and Riener, R. (2013). The effect of haptic guidance and visual feedback on learning a complex tennis task. *Experimental brain research*, 231(3):277–291. *Cited page 5*

[101] Marvel, J. A., Bagchi, S., Zimmerman, M., and Antonishek, B. (2020). Towards effective interface designs for collaborative hri in manufacturing: Metrics and measures. *ACM Transactions on Human-Robot Interaction (THRI)*, 9(4):1–55. *Cited page 21*

[102] Mayer, R. E. (2010). Applying the science of learning to medical education. *Medical education*, 44(6):543–549. *Cited page 40*

[103] Meenink, T., Naus, G., de Smet, M., Beelen, M., and Steinbuch, M. (2013). Robot assistance for micrometer precision in vitreoretinal surgery. *Investigative ophthalmology & visual science*, 54(15):5808–5808. *Cited page 6*

[104] Milot, M.-H., Marchal-Crespo, L., Green, C. S., Cramer, S. C., and Reinkensmeyer, D. J. (2010). Comparison of error-amplification and haptic-guidance training techniques for learning of a timing-based motor task by healthy individuals. *Experimental brain research*, 201(2):119–131. *Cited page 5*

[105] Mishra, P. and Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers college record*, 108(6):1017–1054. *Cited page 68*

[106] Mishra, P., Spiro, R. J., and Feltovich, P. J. (1996). Technology, representation, and cognition: The prefiguring of knowledge in cognitive flexibility hypertexts. *Advances in discourse processes*, 58:287–305. *Cited page 68*

[107] Mondada, L. (2014). Instructions in the operating room: How the surgeon directs their assistant's hands. *Discourse Studies*, 2:131–161. *Cited page 19*

[108] Moorthy, K., Munz, Y., Dosis, A., Hernandez, J., Martin, S., Bello, F., Rockall, T., and Darzi, A. (2004). Dexterity enhancement with robotic surgery. *Surgical Endoscopy and Other Interventional Techniques*, 18(5):790–795. *Cited page 14*

[109] Morel, G., Szewczyk, J., and Vitrani, M.-A. (2013). Comanipulation. *Medical Robotics*, pages 303–350. *3 citations page 15, 16, and 36*

[110] Mota, P., Carvalho, N., Carvalho-Dias, E., Costa, M. J., Correia-Pinto, J., and Lima, E. (2018). Video-based surgical learning: improving trainee education and preparation for surgery. *Journal of surgical education*, 75(3):828–835. *Cited page 40*

[111] Nackman, G. B., Bermann, M., and Hammond, J. (2003). Effective use of human simulators in surgical education1. *Journal of surgical research*, 115(2):214–218. *Cited page 5*

[112] Neumuth, T. (2012). Surgical process modeling-theory, methods, and applications. *Cited page 42*

[113] Neumuth, T. (2017). Surgical process modeling. *Innovative surgical sciences*, 2(3):123–137. *2 citations page 41 and 42*

[114] Nisky, I., Huang, F., Milstein, A., Pugh, C. M., Mussa-Ivaldi, F. A., and Karniel, A. (2012). Perception of stiffness in laparoscopy–the fulcrum effect. *Studies in health technology and informatics*, 173:313. *Cited page 15*

[115] of American Gastrointestinal, S. and Surgeons, E. (2010). Fundamentals of laparoscopic surgery (fls). http://www.flsprogram.org. *Cited page 19*

[116] Oram, D. H. (2006). Basic surgical skills. *Best Practice & Research Clinical Obstetrics & Gynaecology*, 20(1):61–71. *Cited page 3*

[117] Parasuraman, R. and Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human factors*, 39(2):230–253. *Cited page 16*

[118] Parsons, B. A., Blencowe, N. S., Hollowood, A. D., and Grant, J. R. (2011). Surgical training: the impact of changes in curriculum and experience. *Journal of surgical education*, 68(1):44–51. *Cited page 2*

[119] Patti, C. J. and Ellis, C. (2017). Co-constructed interview. *The International Encyclopedia*. *Cited page 44*

[120] Peahl, A. F., Tarr, E. E., Has, P., and Hampton, B. S. (2019). Impact of 4 components of instructional design video on medical student medical decision making during the inpatient rounding experience. *Journal of surgical education*, 76(5):1286–1292. *2 citations page 40 and 88*

[121] Pearle, A. D., Kendoff, D., Stueber, V., Musahl, V., and Repicci, J. A. (2009). Perioperative management of unicompartmental knee arthroplasty using the mako robotic arm system (makoplasty). *American Journal of Orthopedics*, 38(2):16–19. *Cited page 16*

[122] Pelikan, H. R., Cheatle, A., Jung, M. F., and Jackson, S. J. (2018). Operating at a distance-how a teleoperated surgical robot reconfigures teamwork in the operating room. *Proceedings of the ACM on Human-Computer Interaction*, 2(CSCW):1–28. *2 citations page 19 and 44*

[123] Peshkin, M. and Colgate, J. E. (1999). Cobots. *Industrial Robot: An International Journal*. *Cited page 16*

[124] Piromchai, P., Avery, A., Laopaiboon, M., Kennedy, G., and O'Leary, S. (2015). Virtual reality training for improving the skills needed for performing surgery of the ear, nose or throat. *Cochrane Database of Systematic Reviews*, (9). *3 citations page 7, 73, and 89*

[125] Polavarapu, H. V., Kulaylat, A. N., Sun, S., and Hamed, O. (2013). 100 years of surgical education: the past, present, and future. *Bull Am Coll Surg*, 98(7):22–27. *Cited page 19*

[126] Poquet, C., Mozer, P., Vitrani, M.-A., and Morel, G. (2014). An endorectal ultrasound probe comanipulator with hybrid actuation combining brakes and motors. *IEEE/ASME Transactions on Mechatronics*, 20(1):186–196. *Cited page 16*

[127] Pouchelle, M.-C. (2008). *L'hôpital ou le théâtre des opérations*. Seli Arslan. *Cited page 44*

[128] Prabhu, A., Smith, W., Yurko, Y., Acker, C., and Stefanidis, D. (2010). Increased stress levels may explain the incomplete transfer of simulator-acquired skill to the operating room. *Surgery*, 147(5):640–645. *Cited page 73*

[129] Pugh, C. M., Watson, A., Bell Jr, R. H., Brasel, K. J., Jackson, G. P., Weber, S. M., and Kao, L. S. (2009). Surgical education in the internet era. *Journal of Surgical Research*, 156(2):177–182. *Cited page 10*

[130] Pulijala, Y., Ma, M., Pears, M., Peebles, D., and Ayoub, A. (2018). Effectiveness of immersive virtual reality in surgical training—a randomized control trial. *Journal of Oral and Maxillofacial Surgery*, 76(5):1065–1072. *Cited page 8*

[131] Putnam, R. T. and Borko, H. (2000). What do new views of knowledge and thinking have to say about research on teacher learning? *Educational researcher*, 29(1):4–15. *Cited page 68*

[132] Radianti, J., Majchrzak, T. A., Fromm, J., and Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, 147:103778. *6 citations page 2, 6, 8, 40, 73, and 89*

[133] Randell, R., Alvarado, N., Honey, S., Greenhalgh, J., Gardner, P., Gill, A., Jayne, D., Kotze, A., Pearman, A., and Dowding, D. (2015). Impact of robotic surgery on decision making: perspectives of surgical teams. In *AMIA Annual Symposium Proceedings*, volume 2015, page 1057. American Medical Informatics Association. *Cited page 19*

[134] Randell, R., Honey, S., Alvarado, N., Pearman, A., Greenhalgh, J., Long, A., Gardner, P., Gill, A., Jayne, D., and Dowding, D. (2016). Embedding robotic surgery into routine practice and impacts on communication and decision making: a review of the experience of surgical teams. *Cognition, Technology & Work*, 18(2):423–437. *Cited page 19*

[135] Randell, R., Honey, S., Hindmarsh, J., Alvarado, N., Greenhalgh, J., Pearman, A., Long, A., Cope, A., Gill, A., Gardner, P., et al. (2017). A realist process evaluation of robot-assisted surgery: integration into routine practice and impacts on communication, collaboration and decision-making. *Health Services and Delivery Research*, 5(20). *Cited page 19*

[136] Reinkensmeyer, D. J. and Patton, J. L. (2009). Can robots help the learning of skilled actions? *Exercise and sport sciences reviews*, 37(1):43. *Cited page 6*

[137] Ronsmans, C., Graham, W. J., steering group, L. M. S. S., et al. (2006). Maternal mortality: who, when, where, and why. *The lancet*, 368(9542):1189–1200. *Cited page 1*

[138] Sadasivan, S., Greenstein, J. S., Gramopadhye, A. K., and Duchowski, A. T. (2005). Use of eye movements as feedforward training for a synthetic aircraft inspection task. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 141–149. ACM. *Cited page 18*

[139] Sailer, U., Flanagan, J. R., and Johansson, R. S. (2005). Eye–hand coordination during learning of a novel visuomotor task. *Journal of Neuroscience*, 25(39):8833–8842. *Cited page 18*

[140] Schmitt, F., Sulub, J., Avellino, I., Da Silva, J., Barbé, L., Piccin, O., Bayle, B., and Morel, G. (2019). Using comanipulation with active force feedback to undistort stiffness perception in laparoscopy. In *2019 International Conference on Robotics and Automation (ICRA)*, pages 3902–3908. IEEE. *Cited page 16*

[141] Schwan, S. and Riempp, R. (2004). The cognitive benefits of interactive videos: learning to tie nautical knots. *Learning and instruction*, 14(3):293–305. *Cited page 9*

[142] Shariff, U., Seretis, C., Lee, D., and Balasubramanian, S. P. (2016). The role of multimedia in surgical skills training and assessment. *the surgeon*, 14(3):150–163. *3 citations page 9, 40, and 88*

[143] Sheik-Ali, S., Edgcombe, H., and Paton, C. (2019). Next-generation virtual and augmented reality in surgical education: a narrative review. *Surgical technology international*, 33. *Cited page 7*

[144] Shimizu, S., Nakashima, N., Okamura, K., Han, H.-S., and Tanaka, M. (2007). Telesurgery system with original-quality moving images over high-speed internet: expansion within the asia-pacific region. *Journal of Laparoendoscopic & Advanced Surgical Techniques*, 17(5):673–678. *Cited page 3*

[145] Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard educational review*, 57(1):1–23. *2 citations page 68 and 71*

[146] Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational researcher*, 15(2):4–14. *2 citations page 68 and 71*

[147] Silverman, D. (1997). Towards an aesthetics of research. *Qualitative research: Theory, method and practice*, pages 239–253. *Cited page 43*

[148] Smith, S., Torkington, J., Brown, T., Taffinder, N., and Darzi, A. (2002). Motion analysis. *Surgical endoscopy*, 16(4):640–645. *Cited page 17*

[149] Spiro, R. J. et al. (2012). Cognitive flexibility and hypertext: Theory and technology for the nonlinear and multidimensional traversal of complex subject matter. In *Cognition, education, and multimedia*, pages 177–220. Routledge. *Cited page 68*

[150] Stark, M., Gerli, S., and Di Renzo, G. C. (2006). The ten-step vaginal hysterectomy. *Prog Obstet Gynaecol*, 17:358–368. *Cited page 48*

[151] Stienen, M. N., Joswig, H., Jucker, D., Hildebrandt, G., Schaller, K., and Gautschi, O. P. (2015). Anterior cervical discectomy and fusion: is surgical education safe? *Acta neurochirurgica*, 157(8):1395–1404. *Cited page 2*

[152] Surgical, I. (2019). Intuitive surgical announces preliminary fourth quarter and full year 2018 results. https://isrg.intuitive.com/news-releases/news-release-details/intuitive-surgical-announces-preliminary-fourth-quarter-and-4.
Cited page 14

[153] Sweller, J., Van Merrienboer, J. J., and Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational psychology review*, 10(3):251–296. *Cited page 9*

[154] Taylor, J. A. and Ivry, R. B. (2014). Cerebellar and prefrontal cortex contributions to adaptation, strategies, and reinforcement learning. In *Progress in brain research*, volume 210, pages 217–253. Elsevier. *Cited page 6*

[155] Taylor, R., Jensen, P., Whitcomb, L., Barnes, A., Kumar, R., Stoianovici, D., Gupta, P., Wang, Z., Dejuan, E., and Kavoussi, L. (1999). A steady-hand robotic system for microsurgical augmentation. *The International Journal of Robotics Research*, 18(12):1201–1210. *Cited page 16*

[156] Torterotot, C. P., Vitrani, M., and Morel, G. (2014). Proximal comanipulation of a minimally invasive surgical instrument to emulate distal forces. In *Proceedings of the 4th Joint Workshop on New Technologies for Computer/Robot Assisted Surgery (CRAS2014)*, pages 48–51. *Cited page 24*

[157] Toussaint, B.-M., Luengo, V., and Jambon, F. (2015a). Understanding perceptual-gestural knowledge in tel systems with eye-tracking. *Revista Romana de Interactiune Om-Calculator*, 8(4):321–340. *Cited page 42*

[158] Toussaint, B.-M., Luengo, V., Jambon, F., and Tonetti, J. (2015b). From heterogeneous multisource traces to perceptual-gestural sequences: The petra treatment approach. In *International Conference on Artificial Intelligence in Education*, pages 480–491. Springer. *2 citations page 42 and 67*

[159] Tsuda, S., Scott, D., Doyle, J., and Jones, D. B. (2009). Surgical skills training and simulation. *Current problems in surgery*, 4(46):271–370.
2 citations page 73 and 87

[160] Tsumugiwa, T., Yokogawa, R., and Hara, K. (2002). Variable impedance control based on estimation of human arm stiffness for human-robot cooperative calligraphic task. In *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292)*, volume 1, pages 644–650 vol.1.
Cited page 21

[161] Vadcard, L. (2013). Étude didactique de la dialectique du travail et de la formation au bloc opératoire. *Éducation et didactique*, 7(7-1):117–146.
2 citations page 45 and 47

[162] Vadcard, L. (2019). Habilitation à diriger des recherches en sciences de l'education et de la formation, université de bourgogne franche comté "vers une didactique des gestes technique - enjeux pour la formation professionnelle en santé". *Cited page 37*

[163] Vannaprathip, N., Haddawy, P., Schultheis, H., and Suebnukarn, S. (2021). Intelligent tutoring for surgical decision making: a planning-based approach. *International Journal of Artificial Intelligence in Education*, pages 1–32. *2 citations page 42 and 67*

[164] Vergnaud, G. (1990). Catégories logiques et invariants opératoires. *Archives de psychologie (Genève)*, 58(225):145–149. *2 citations page 46 and 62*

[165] Vergnaud, G. (1992). Conceptual fields, problem solving and intelligent computer tools. In *Computer-based learning environments and problem solving*, pages 287–308. Springer. *5 citations page 46, 47, 62, 74, and 77*

[166] Vergnaud, G. (2011). La pensée est un geste comment analyser la forme opératoire de la connaissance. *Enfance*, (1):37–48. *2 citations page 48 and 57*

[167] Vergnaud, G. and Récopé, M. (2000). De revault d'allonnes à une théorie du schème aujourd'hui. *Psychologie française*, 45(1):35–50. *Cited page 47*

[168] Wadsworth, B. J. (1996). *Piaget's theory of cognitive and affective development: Foundations of constructivism.* Longman Publishing. *Cited page 74*

[169] Wasen, K. (2010). Replacement of highly educated surgical assistants by robot technology in working life: Paradigm shift in the service sector. *International Journal of Social Robotics*, 2(4):431–438. *Cited page 19*

[170] Webb, J. et al. (1970). Observation as a methodology. *Cited page 44*

[171] Weiser, T. G., Regenbogen, S. E., Thompson, K. D., Haynes, A. B., Lipsitz, S. R., Berry, W. R., and Gawande, A. A. (2008). An estimation of the global volume of surgery: a modelling strategy based on available data. *The Lancet*, 372(9633):139–144. *Cited page 1*

[172] Wilson, M., McGrath, J., Vine, S., Brewer, J., Defriend, D., and Masters, R. (2010). Psychomotor control in a virtual laparoscopic surgery training environment: gaze control parameters differentiate novices from experts. *Surgical endoscopy*, 24(10):2458–2464. *3 citations page 18, 21, and 25*

[173] Wilson, M. R., Poolton, J. M., Malhotra, N., Ngo, K., Bright, E., and Masters, R. S. (2011a). Development and validation of a surgical workload measure: the surgery task load index (surg-tlx). *World journal of surgery*, 35(9):1961. *Cited page 21*

[174] Wilson, M. R., Vine, S. J., Bright, E., Masters, R. S., Defriend, D., and McGrath, J. S. (2011b). Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: a randomized, controlled study. *Surgical endoscopy*, 25(12):3731–3739. *2 citations page 18 and 25*

[175] Xeroulis, G., Dubrowski, A., and Leslie, K. (2009). Simulation in laparoscopic surgery: a concurrent validity study for fls. *Surgical endoscopy*, 23(1):161–165. *Cited page 17*

[176] Yoganathan, S., Finch, D., Parkin, E., and Pollard, J. (2018). 360 virtual reality video for the acquisition of knot tying skills: a randomised controlled trial. *International Journal of Surgery*, 54:24–27. *Cited page 8*

[177] Yule, S., Flin, R., Paterson-Brown, S., and Maran, N. (2006). Non-technical skills for surgeons in the operating room: a review of the literature. *Surgery*, 139(2):140–149. *Cited page 19*

[178] Zhou, M., Tse, S., Derevianko, A., Jones, D., Schwaitzberg, S., and Cao, C. (2012). Effect of haptic feedback in laparoscopic surgery skill acquisition. *Surgical endoscopy*, 26(4):1128–1134. *Cited page 6*