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Integrating VR, AR, and Haptics in Basic Surgical Skills Training: A Review and Perspective

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ABSTRACT Traditional surgical training faces challenges related to sustainability, cost, and ethical considerations. Limited access to resources, ethical concerns about cadaver-based learning, limited availability of surgical cases, and the high costs associated with hands-on training impede the effectiveness and accessibility of surgical education. Despite these challenges, the need for direct tactile experience remains critical, as it fosters the development of essential motor skills and tactile abilities vital for surgical practice. However, advancements in immersive technologies such as virtual reality (VR), augmented reality (AR), and haptics offer a promising solution to address these challenges. VR and AR technologies offer realistic, controlled environments where learners can visualise anatomical structures and practice surgical procedures without risks. The integration of haptic feedback in these immersive simulations further enriches the learning process by adding the sense of touch and physical interaction, aiding in mastering critical surgical skills. The incorporation of immersive technologies in surgical training presents an opportunity to address the constraints of conventional methods. These technologies offer the possibility of creating platforms that replicate real-life surgical scenarios, allowing learners to hone their skills and build confidence in a safe and controlled environment. Moreover, immersive learning offers an ethical alternative to cadaver-based training and extends access to training materials irrespective of geographical limitations. Such an approach allows for step-based training, where students may begin acquiring skills through immersive learning, then move to special surgical simulators, and finally to patients. This article deals with the impact of immersive technologies such as VR, AR, and haptics on reshaping conventional surgical training, by focusing specifically on basic surgical skills. Targeting educators, medical experts, and involved parties, the article aims to stimulate additional exploration and adoption of immersive technologies to elevate surgical competencies and patient care standards.

INDEX TERMS Surgical education, immersive technologies, haptics, tactile learning.

I. INTRODUCTION

TRAINING surgeons has always been a resource-intensive and ethically challenging endeavour. The need for hands-on experience in high-stakes environments demands access to cadavers, live animals, or patients, all of which pose significant logistical, financial, and moral constraints. Additionally, the increasing complexity of modern surgical procedures and the growing emphasis on patient safety have further strained traditional training methods. These challenges underscore the urgent need for innovative approaches to surgical education that can provide realistic, risk-free practice opportunities.

In the last two decades, advancements in virtual reality (VR), augmented reality (AR), and haptics have promised to revolutionise surgical training. These technologies offer immersive environments where trainees can develop their skills without compromising patient safety. Commercial products like the Touch Surgery [2] have demonstrated the potential of these innovations to enhance medical education. However, most of these applications rely on expensive setups, making them inaccessible to a broad audience of students. Furthermore, many existing systems are designed specifically for robotic-assisted or minimally invasive surgeries, as these tools are easier to instrument and sensorise, leaving other tactile-intensive procedures less explored.

Tactile interaction is essential in many science, technology, engineering, and mathematics (STEM) disciplines where laboratory activities and hands-on engagement with tools or objects are essential [3]. For instance, medical students must learn to identify lymph node enlargement through palpation, engineering students require soldering skills for electronic components, and art students need to develop proficiency in manipulating clay. The integration of haptics into educational tools has the potential to bridge the gap between theoretical knowledge and practical skills, making it a critical area of exploration for the future of surgical training.

The recent COVID-19 pandemic further highlighted the global shortage of medical personnel and the pressing need for online and remote training solutions. In response to these challenges, various initiatives have emerged. One notable example is the AugmentedWearEdu project [4], a collaborative effort among researchers from multiple European countries, funded by the European Community. This initiative aims at enhancing the quality of distance learning by integrating haptic interfaces to create digital content enriched with tactile interaction.

Within the AugmentedWearEdu project [4], three specific modes of utilising digitised touch are considered, as shown in Figure 1. The first mode, called Remote Touch, involves the teacher touching or manipulating objects while wearing gloves equipped with sensors that record tactile interactions, such as the forces exchanged with the object, its temperature, and its roughness. These interactions, once digitised, can be reproduced on the students' hands using haptic interfaces. Additionally, this approach allows for a reversal of the interaction paradigm, where students can send tactile feedback to the teacher, enabling the teacher to assess whether the students' manipulations meet expectations. The second mode focuses on remote Guidance of a gesture. This approach allows an instructor to guide a student's arm to teach them how to perform a gesture correctly, such as gripping and moving a tool. Through haptic interfaces, it is possible to create stimuli that suggest directions and body postures, which can be used to indicate or correct a specific movement. Finally, the third mode involves creating a Physical Interaction in virtual or augmented reality where students can interact with objects and tools. For instance, it is possible to reconstruct a chemical laboratory and have students perform experiments by interacting with virtual materials and tools. This immersive approach not only enhances the learning experience but also allows students to safely explore and manipulate complex environments and processes. From these three examples, a range of potential applications can be envisioned, which may contribute to making distance learning experiences more immersive and closer to real-life interactions. Among these, the importance of touch is especially significant in fields like medical training, where tactile skills are critical.

Importance of touch and multi-modal immersion for medical training. Touch plays one of the major roles in medical training. It is important not only when performing a physical examination of the patient but also when encountering and communicating with patients. Touch allows clinicians to assess various physical characteristics such as temperature, texture, and tenderness, which are crucial for accurate diagnosis and treatment planning. Techniques like palpation and percussion [5] rely heavily on the sense of touch to detect abnormalities such as masses, organ enlargement (i.e., hepatomegaly and splenomegaly), or fluid accumulation (ascites). Furthermore, touch is essential in building trust with patients. A comforting touch can convey empathy and compassion, helping to alleviate patient anxiety and create a more positive clinical experience. In medical training, the sense of touch is critical for acquiring and performing various clinical skills and procedures, such as administering injections, hand washing, and basic surgical procedures.

One key aspect of enhancing these educational experiences is the integration of multi-modal immersion, which involves engaging multiple senses simultaneously—such as sight, sound, and touch. Research has shown that multi-modal learning can significantly improve comprehension and retention by providing a richer and more engaging environment for students. By combining visual, auditory, and tactile stimuli, multi-modal immersion creates a more holistic and realistic learning experience, thereby reinforcing concepts and skills more effectively. This approach is particularly beneficial in fields that require a high degree of spatial awareness and hands-on practice, such as medicine.

Rationale about the gestures of inspection, auscultation, palpation, and percussion of the abdomen. Physical examination (inspection, auscultation, palpation, and percussion) has been one of the main methods of patient evaluation for many years [6]. It starts with visually inspecting the area of interest (e.g., the abdomen) and is followed by auscultation (listening to various sounds in the body, such as bowel movements in the abdomen), palpation, and finally, percussion. Touch in inspection and auscultation is only applied in a limited manner. However, in the case of palpation and

(a) Remote touch. (b) Guidance. (c) Physical interaction in VR.

FIGURE 1: Three specific modes of utilising digitised touch studied in the AugmentedWearEdu project [4].

percussion, touch becomes very important for localising pain and evaluating abdominal tenderness, among other things.

Medical students are taught to perform physical examinations during their undergraduate studies. Unfortunately, due to fast-developing technologies, time constraints, and other obstacles, fewer and fewer postgraduates and even physicians are able to perform physical examinations correctly. Physical examination is crucial for making accurate and early diagnoses and for developing further diagnostic and treatment plans. Correctly performed and comprehensive physical examinations might help avoiding unnecessary instrumental and laboratory tests. Conversely, incorrect physical examinations might even threaten patient safety [7].

ImmersiveSurgicalEdu. Building on the foundation of tactile importance and multi-modal immersion in medical training, our new project, "Beyond the Classroom: Virtual Reality, Augmented Reality and Haptics for Enhanced Surgical Training and Education (ImmersiveSurgicalEdu)" [8], aims to design, build, and test a haptic-enabled immersive tool for basic surgical education. This project integrates cutting-edge virtual reality (VR) and augmented reality (AR) capabilities with wearable haptic devices, providing students with a realistic and immersive learning experience in a safe and controlled environment. The goal is to enhance learning outcomes and improve patient care by incorporating haptics into immersive learning situations, giving students a tactile experience that closely simulates real surgical procedures. This approach is expected to lead to better surgical outcomes and increased patient safety.

Contribution. The objective of this paper is to position tools such as Virtual Reality (VR), Augmented Reality (AR), and haptics as core components of modern training for basic surgical skills. These technologies have the potential to revolutionise surgical education by providing immersive, interactive, and tactile experiences that are critical for developing the skills necessary for successful surgical practice. To achieve this, the manuscript offers a comprehensive and structured review of these emerging technologies, analysing their strengths, limitations, and potential impact on the future of surgical education. Furthermore, the paper provides actionable guidelines for the effective implementation of VR, AR, and haptics in both research and practical settings, ensuring that these tools are integrated in a way that maximises their educational value.

This paper is organised as follows. The medical needs for effective surgical training are explained in Section II. Challenges in traditional surgical training are outlined in Section III. New technologies for medical training, i.e., VR, AR, and haptics, are described in Section IV. An organised set of directions/road-map on how to better integrate AR/VR/haptics for medical training is presented in Section V. Finally, conclusions and future work are outlined in Section VI.

II. MEDICAL NEEDS FOR BASIC SURGICAL TRAINING

The physical examination consists of four main steps and the whole examination is performed when the patient is lying in the supine position on an examining table or bed [9]:

- Inspection. Contour and colour of the skin is inspected. Any abnormalities (also specific signs, such as Cullen and Turner signs) are noted. In case of abdomen inspection, the abdomen is checked for any scars and masses. Touch is not applied during this step.
- Auscultation. In this step a stethoscope is used to listen and evaluated bowel sounds, which can change in case of peritonitis, bowel obstruction and other diseases. Touch is applied by compressing the stethoscope to the abdominal wall. However, no direct touch with a hand on the skin and abdominal wall is conducted.
- Palpation. This is the main step of physical examination. By placing fingers and later the hand (both hands) on the abdomen, and applying pressure, different aspects are evaluated: scars, masses, pain, abdominal tenderness and other. Pressure and resistance are the main physical characteristics of palpation.
- Percussion. The physical examination is finished by percussion. By tapping with fingers, the abdominal wall size and location of organs might be evaluated.

It is estimated that a specialist in training must perform over 750 operations to achieve a baseline proficiency in practical skills [10]. This extensive practice ensures the acquisition of essential competencies such as hand-eye coordination, tactile sensitivity, and procedural decision-making. In addition to theoretical knowledge, surgical training emphasises apprenticeship, where learners, alongside experienced surgeons, observe procedures, assist, and gradually perform basic and advanced procedures [11]. The association between performed surgical procedures and patient outcomes in the last decade is described in multiple studies [12], showing that the higher number of performed surgical procedures is associated with less complications, shorter in-hospital stay and lower mortality.

The current training procedure. Achieving professional status as a surgeon requires rigorous adherence to both theoretical knowledge and practical experience. Typically, after completing undergraduate studies (usually spanning 5-6 years in most programs), surgical training programs themselves last 5 to 6 years, with an additional 1 to 3 years of fellowship training for specialisation. This comprehensive training ensures that surgeons are equipped not only with technical proficiency but also with the resilience and adaptability needed to excel in the field of surgery.

Limits of the current training procedure. The advantage and disadvantage of the apprenticeship method is that specialist skills are developed while working with real patients, tissues, and organs. However, this teaching method does not tolerate mistakes due to lack of experience, methodological knowledge, tactical interference, inadequate stress management, and other factors related to the execution of theoretical and practical actions, especially when encountering a complex clinical case for the first time. Moreover, relying primarily on apprenticeship as the main method of preparing and educating surgeons significantly limits the availability of surgical studies, prolongs the preparation of specialists, and increases the likelihood of professional risks and health hazards during work [11].

Some surgical programs have implemented training using laboratory animals (such as pigs, rabbits, and mice) or donated bodies. However, these methods present numerous legal and ethical issues. Additionally, the high cost and limited number of surgical procedures available play a crucial role in choosing the training method [13], [14]. Medical and surgical literature, surgical videos, and medical simulators are still an integral parts of most training programs.

Unfortunately, not all surgical training programs are able to implement all of the aforementioned training methods, leading to various issues as described in the following sections.

A. LIMITATIONS OF CURRENT TRAINING PROCEDURES

Regarding training procedures, surgeons are encountering numerous limitations. In the face of these constraints, surgical trainees confront a myriad of difficulties, with variations observed across continents, countries, and medical centres. Despite this diversity, common issues persist. Formerly confined to high-volume university hospitals, surgical training faces a significant setback as the increasing number of students and the specialisation focus of high-volume hospitals compromise the foundational training of essential surgical skills [15].

Challenges in surgical training may vary between the perspectives of trainees and mentors or senior surgeons [16]. The constant evolution of surgical techniques, such as laparoscopic and robotic surgery, adds complexity to training, necessitating the evolution of traditional training and education methods. The number of open surgeries and other less complex interventions is decreasing, while the number of complex surgeries is increasing. As a result, surgical trainees are exposed less to basic operations and fundamental training and more to complex and challenging tasks.

Common challenges reported by surgical trainees include:

- limited availability of cases for training.
- concerns about the quality and quantity of performed operations.
- insufficient time allocated for attending conferences and surgical courses.

Even senior surgeons and educators acknowledge that one of the main challenges in surgical training is the limited number of cases available for trainees [17]. Equally significant is the constraint on time required to acquire a high level of surgical skills. Other authors also identify similar challenges in surgical training, such as:

- limited access to surgeries and procedures.
- time constraints for training.
- ethical considerations regarding practising and training on live patients.

Hospitals are compelled to attain predefined outcomes, such as reducing the time until diagnosis, minimising the duration of in-hospital stays, and improving the efficiency of operating theatre operations (faster surgeries, shorter breaks). However, these factors have a detrimental effect on surgical training, as senior surgeons become more focused on achieving numerical targets rather than prioritising the training of future surgeons. Mistakes during training on live patients can have severe consequences not only for patients but also for trainees, educators, hospitals, and medical universities. Considering all the challenges mentioned, there is an increasing demand for alternative training methods beyond surgical theatres and departments.

III. CHALLENGES IN TRADITIONAL SURGICAL TRAINING

In this section, the most relevant challenges in traditional surgical training are outlined, as shown in Table 1.

A. SUSTAINABILITY ISSUES

Sustainability issues in traditional surgical training encompass a range of challenges related to environmental impact, resource consumption, energy use, and overall long-term viability [18]. A detailed exploration of these sustainability issues is provided in the following:

- Environmental Impact: The environmental impact of traditional surgical training is a multifaceted challenge,

TABLE 1: Challenges in Traditional Surgical Training

No.	Challenges	Summary
1	Sustainability Issues	• Environmental Impact • Resource Consumption • Energy Consumption • Limited Scalability • Financial Sustainability • Technological Obsolescence
2	Financial Issues	• High Operational Expenses • Cadaver Procurement and Maintenance • Equipment Acquisition and Upkeep • Training Personnel Expenses • Limited Accessibility for Aspiring Surgeons • Limited Scalability • Ineffectiveness of Conventional Method
3	Geographical Issues	• Centralisation of Training Centres • Travel-Related Barriers • Access to Diverse Surgical Cases • Healthcare Workforce Distribution • Telecommunication and Connectivity Challenges • Cultural and Linguistic Considerations
4	Ethical Concerns	• Cadaveric Learning and Respect for Donors • Patient Consent in Hands-On Training • Emotional Impact on Trainees • Ensuring Diversity and Inclusivity • Informed Consent for Innovative Procedures • Global Health Disparities and Access • Balancing Educational Needs and Ethical Principles • Adapting to Changing Ethical Norms

primarily arising from the use of cadavers and live animals. The preservation process involving embalming fluids and chemicals raises ecological concerns, particularly regarding their disposal. Ensuring the proper and environmentally responsible disposal of cadavers, as well as the associated chemicals, becomes imperative to prevent soil and water pollution. Additionally, the reliance on disposable materials, such as single-use surgical instruments and protective gear, contributes significantly to medical waste. Sustainable alternatives that promote the reduction, reuse, and recycling of materials are essential to minimise the environmental footprint of traditional cadaver-based training [19], [20].

- Resource Consumption: The traditional approach to surgical training is marked by resource-intensive practices, particularly concerning the consumption of disposable materials [21]. Single-use items, including surgical instruments, gloves, and drapes, contribute to significant waste generation and require substantial raw materials for production. Addressing resource consumption challenges involves not only exploring alternatives to disposable items but also implementing comprehensive waste management strategies. This includes initiatives to reduce overall waste generation, promote recycling, and explore the use of sustainable materials in the production of surgical instruments and equipment.
- Energy Consumption: Energy consumption is a critical aspect of sustainability in traditional surgical training facilities. The operation of specialised equipment, lighting systems, and climate control mechanisms contributes to high energy usage. Adopting sustainable practices in energy management is crucial, ranging from the integration of energy-efficient technologies to the exploration of renewable energy sources. This transition not only aligns with environmental sustainability goals but also has the potential to reduce operational costs for surgical training facilities, enhancing their overall economic sustainability.
- Limited Scalability (resources): The scalability of traditional surgical training methods is hindered by the substantial infrastructure requirements, such as anatomy laboratories and surgical suites. The construction and maintenance of these facilities are resource-intensive, limiting their proliferation, especially in regions with limited resources [22]. To address scalability challenges, a paradigm shift towards innovative, technology-driven solutions is essential. Virtual platforms, simulation technologies, and decentralised training methods can democratise access to surgical education, making it more scalable and adaptable to diverse global settings.
- Financial Sustainability: Financial sustainability in traditional surgical training is undermined by the high operational costs associated with maintaining specialised facilities and equipment. Budgetary constraints within educational institutions and healthcare systems further compound the challenge. Achieving financial sustainability involves a comprehensive evaluation of cost-effective alternatives, exploring innovative funding models, and potentially leveraging partnerships and collaborations. Striking a balance between the need for quality education and fiscal responsibility is crucial for the long-term financial viability of surgical training programs [23].
- Technological Obsolescence: The dynamic nature of surgical technologies introduces concerns related to equipment obsolescence in traditional training. The lifecycle management of equipment, including timely upgrades and sustainable disposal practices, is vital for addressing technological sustainability challenges. Embracing emerging technologies, such as virtual reality and augmented reality, not only enhances the educational experience but also offers a pathway to sustainable practices by providing adaptable and upgradable solutions. Integrating these technologies ensures that surgical training remains at the forefront of advancements, aligning with the evolving landscape of surgical

practice [24].

B. FINANCIAL CHALLENGES

Financial challenges in traditional surgical training are complex and span various aspects of the educational process, from infrastructure to personnel and accessibility [25]. A detailed examination of these challenges sheds light on the financial burdens faced by educational institutions and healthcare systems:

- High Operational Expenses: Traditional surgical training requires dedicated spaces like anatomy labs, simulation centres, and surgical suites. The construction, maintenance, and utility expenses for these specialised facilities contribute significantly to operational costs. The need for state-of-the-art facilities to simulate real surgical environments further increases the financial burden on institutions [26].
- Cadaver Procurement and Maintenance: The use of cadavers is a cornerstone of traditional surgical training, but it comes with substantial financial implications. Procuring ethically sourced cadavers involves legal considerations and associated expenses. Moreover, maintaining cadavers through embalming processes and ensuring a conducive learning environment demands specialised facilities, trained personnel, and ongoing resources. No less cost intensive is also live animal use in surgical training.
- Equipment Acquisition and Upkeep: The acquisition and maintenance of surgical equipment are key financial challenges. High-fidelity simulation devices, surgical instruments, and other technological tools come with considerable price tags. Keeping this equipment up-to-date with the latest advancements in surgical technology requires ongoing investment, adding to the overall financial burden of traditional training [27].
- Training Personnel Expenses: Skilled trainers, including surgeons and educators, are essential for hands-on surgical training. Recruiting and retaining these experts demand competitive salaries and benefits. Continuous professional development to keep trainers abreast of evolving surgical techniques adds further to personnel-related expenses, constituting a substantial portion of the overall training costs [27].
- Limited Accessibility for Aspiring Surgeons: The financial requirements of traditional surgical training create barriers for aspiring surgeons. Tuition fees, associated materials, and potential relocation costs make these programs inaccessible to individuals from economically disadvantaged backgrounds [28]. This lack of financial accessibility contributes to a potential underrepresentation of diverse talents within the surgical profession.
- Limited Scalability (students): Traditional surgical training methods may struggle to scale up to meet increasing demand. Expanding programs to accommodate a growing number of students or extending training to underserved regions requires substantial financial investments [29]. The resource-intensive nature of traditional training hampers scalability, hindering efforts to address the global demand for skilled surgical professionals.
- Ineffectiveness of Conventional Methods: The traditional model's variability in learning experiences and limited opportunities for procedural repetition may lead to inefficiencies in skill development. Ineffectiveness in skill acquisition can result in extended training periods and the need for additional financial resources to ensure competency. This inefficiency adds to the overall financial burden of traditional surgical education.

To address these cost-related challenges, there is a growing interest in exploring cost-effective alternatives and leveraging emerging technologies, such as virtual reality (VR), augmented reality (AR), and haptics, which offer the potential to reduce some of the financial burdens associated with traditional surgical training. These technologies can provide realistic, repeatable simulations without the need for extensive physical resources, potentially mitigating several cost-related challenges in surgical education.

C. GEOGRAPHICAL ISSUES

Geographical issues in traditional surgical training pose significant challenges related to access, equity, and regional disparities [30]. These challenges can be delineated in more detail:

- Centralisation of Training Centres: Traditional surgical training centres are often concentrated in urban or well-developed areas, leading to a geographic centralisation of educational resources. This centralisation limits access for individuals residing in rural or underserved regions, creating disparities in the availability of comprehensive surgical education [31]. Trainees from distant areas may face additional challenges related to travel costs, accommodation, and relocation, further exacerbating geographical disparities.
- Travel-Related Barriers: Geographical distances between training centres and trainees' locations contribute to significant travel-related barriers. The necessity for trainees to travel long distances to attend workshops, conferences, or hands-on training sessions not only incurs additional costs but also poses logistical challenges, particularly for those in remote areas. This can deter individuals from pursuing surgical education due to the associated financial and practical constraints.
- Access to Diverse Surgical Cases: Geographical variations impact the types and complexity of surgical cases available for training. Trainees in specific regions may have limited exposure to diverse and complex surgical procedures, affecting the breadth and depth of their experience. This variability in case exposure can hinder the development of well-rounded surgical skills, particularly in regions with fewer specialised medical facilities.

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- Healthcare Workforce Distribution: Geographical issues extend to the distribution of the healthcare workforce. Regions with limited access to surgical training programs may also face shortages in qualified surgical instructors and mentors. This uneven distribution of expertise further compounds the challenge of providing consistent and high-quality surgical education across diverse geographical areas.
- Telecommunication and Connectivity Challenges: The integration of technology, such as virtual or remote surgical training, as a solution to geographical disparities may face challenges in regions with inadequate telecommunication infrastructure. Limited internet connectivity or poor network reliability can hinder the seamless implementation of distance learning initiatives, limiting the effectiveness of efforts to overcome geographical barriers.
- Cultural and Linguistic Considerations: Geographical diversity often brings about cultural and linguistic variations. Traditional surgical training methods may not adequately account for these differences, potentially leading to challenges in communication, understanding, and adapting teaching methodologies to suit diverse cultural contexts. Ensuring inclusivity and cultural sensitivity in surgical education is crucial for overcoming these geographical hurdles.

Addressing geographical issues in surgical training requires a multifaceted approach. This includes the development of decentralised training programs, the implementation of virtual and remote learning opportunities, and efforts to distribute educational resources more equitably across diverse regions. By acknowledging and actively working to mitigate these geographical challenges, the surgical education community can contribute to a more inclusive and accessible training environment for aspiring surgeons worldwide.

D. ETHICAL CONSIDERATIONS WITH TRADITIONAL METHODS

Ethical considerations in traditional surgical training encompass a range of concerns that touch upon patient consent, respect for human donors, trainee well-being, and the broader societal implications of these practices. A detailed exploration of these topics is presented in the following:

- Cadaveric Learning and Respect for Donors: The use of cadavers for anatomical dissection in traditional surgical training raises ethical considerations regarding the respect and dignity owed to individuals who have donated their bodies for educational purposes. Ensuring proper consent processes, clear communication with donors or their families, and maintaining the utmost respect for the deceased are essential ethical considerations. Striking a balance between the educational needs of trainees and the ethical treatment of human donors is an ongoing challenge.
- Patient Consent in Hands-On Training: In traditional surgical training, trainees often practice on live patients under the supervision of experienced surgeons. Ensuring informed and voluntary consent from patients for these procedures is crucial. Ethical concerns arise when patients might feel pressured to consent due to the hierarchical nature of the medical environment. Respecting patient autonomy, providing comprehensive information, and ensuring the voluntary nature of participation are vital ethical considerations.
- Emotional Impact on Trainees: Traditional surgical training, especially hands-on experiences such as cadaver dissection, can have a profound emotional impact on trainees. Witnessing or participating in surgeries on live patients may also evoke strong emotions. Ethical considerations include acknowledging and addressing the potential psychological challenges faced by trainees, providing adequate psychological support, and ensuring their emotional well-being throughout their training.
- Ensuring Diversity and Inclusivity: Ethical considerations extend to ensuring diversity and inclusivity in surgical training. It's crucial to address potential biases in the selection of trainees and instructors, providing equal opportunities for individuals from diverse backgrounds. A lack of diversity can lead to disparities in healthcare outcomes and perpetuate social injustices, emphasising the ethical imperative for inclusivity in surgical education.
- Global Health Disparities and Access: Ethical considerations in surgical training extend globally, particularly concerning disparities in healthcare resources and access. Traditional training methods may be concentrated in certain regions, exacerbating global health inequities. Ethically addressing these disparities involves efforts to extend surgical education resources to underserved areas, promoting global collaboration, and fostering initiatives that bridge the gap in surgical expertise across different regions.
- Balancing Educational Needs and Ethical Principles: Striking a balance between the educational needs of trainees and ethical principles is an ongoing challenge in surgical training. Traditional methods often involve a degree of hands-on experience, but ethical considerations demand careful navigation to ensure that the educational benefits do not compromise patient safety, respect for human donors, or the well-being of trainees.
- Adapting to Changing Ethical Norms: Ethical considerations in surgical training evolve alongside changing societal norms and attitudes toward medical practices. Traditional methods may need adaptation to align with contemporary ethical standards, emphasising continuous ethical reflection, adaptation to new ethical norms, and ensuring that training practices are in harmony with evolving societal expectations.

IV. NEW TECHNOLOGIES FOR MEDICAL TRAINING

Advancements in technology have revolutionised medical training, particularly in surgical education. Virtual Reality (VR), Augmented Reality (AR), and haptics are at the forefront of these innovations, offering immersive and interactive platforms for surgical trainees. These technologies address many limitations of traditional training methods by providing realistic simulations without the ethical and practical constraints of cadaver-based learning. In this section, we present a state-of-the-art survey of VR, AR, and haptic applications in medical training, focusing on their implementation, benefits, and challenges in surgical education.

A. VIRTUAL REALITY IN SURGICAL TRAINING

1) Overview

Virtual Reality (VR) creates a fully immersive, computer-generated environment that simulates real-life surgical scenarios. This technology allows trainees to practice procedures repeatedly in a risk-free setting, enhancing their skills and confidence before operating on actual patients. The studies summarised in Table 2 demonstrate the effectiveness of VR in various surgical disciplines, while also presenting some contrasting views on its efficacy.

2) Analysis

Lohre et al. [32] conducted a randomised controlled trial demonstrating that immersive VR training significantly improved orthopedic surgical skills and knowledge among senior residents. The study highlighted the benefits of immediate feedback and the ability to practice in a risk-free environment.

In a separate study, Lohre et al. [34] focused on complex skill acquisition using immersive VR training. Their randomised controlled trial showed that senior surgical residents who trained with VR demonstrated superior performance in complex orthopedic procedures compared to those who received traditional training. The authors emphasised the importance of VR in mastering advanced surgical skills.

McKechnie et al. [33] discussed the role of VR platforms in maintaining surgical training during the COVID-19 pandemic. VR allowed trainees to continue developing their skills remotely when access to operating rooms was restricted, highlighting the adaptability of VR training in unprecedented circumstances.

Cevallos et al. [35] examined the efficacy of VR in preparing surgical trainees for pinning of a slipped capital femoral epiphysis (SCFE). Participants were randomised into a standard study guide group and a VR training group using Osso VR with real-time feedback from an attending surgeon. The VR group demonstrated improved performance metrics, such as reduced time to completion and fewer errors. This suggests that VR training is potentially more effective than traditional preparatory methods. However, as a pilot study with a small sample size, further research is needed to validate these findings.

Munawar et al. [36] explored the use of fully immersive VR with haptic feedback in skull-base surgery training. Their study involved surgical residents using a VR system that provided realistic simulations of skull-base surgical procedures with integrated haptic feedback. The results indicated that participants showed improved spatial understanding and surgical skills after training. The study also highlighted challenges such as technical complexity and the need for specialised equipment but emphasised the potential of VR with haptics to enhance surgical education in complex anatomical areas.

3) Pros and Cons

The advantages of using VR in surgical training include:

- **Risk-Free Environment**: Allows trainees to practice without risk to patients.
- **Enhanced Learning Efficiency**: Provides immediate feedback and allows repetitive practice.
- **Accessibility**: Can be accessed remotely, facilitating training during restrictions (e.g., COVID-19 lockdowns).
- **Realistic Simulation**: Advanced VR can provide realistic anatomical models and scenarios.
- **Inclusion of Haptic Feedback**: Systems like those used by Munawar et al. integrate tactile sensations, enhancing realism.

The disadvantages and limitations of employing VR in surgical training include:

- **High Initial Costs**: Investment in VR equipment and software can be substantial.
- **Technical Challenges**: Requires technical expertise to set up and maintain.
- **Limited Validation**: Some studies indicate a need for more evidence on the effectiveness and transferability of VR training.
- **Equipment Dependence**: Requires access to VR hardware, which may not be available to all trainees.
- **Complexity of Advanced Systems**: Incorporating haptic feedback adds to technical complexity and costs.

4) Sensing and Recording

In VR surgical training, **sensing and recording** involve capturing the trainee's movements and interactions within the virtual environment. This is achieved using motion-tracking devices such as handheld controllers, gloves, or motion sensors integrated into VR systems. These devices record data on instrument manipulation, hand movements, and procedural steps, which can be used for performance assessment [36].

5) Rendering and Playing

Rendering and playing involve generating the immersive virtual environment and delivering it to the trainee through VR headsets and displays. High-fidelity graphics simulate anatomical structures and surgical scenarios. Advanced VR systems, like the one used by Munawar et al. [36], incorporate haptic feedback to enhance realism by simulating tactile

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TABLE 2: Summary of Studies on VR in Surgical Training

Reference	Surgical Application	Technology Used	Study Type	Participants	Outcomes	Pros	Cons
Lohre et al. (2020) [32]	Orthopedic Surgical Skills	Immersive VR training	RCT	Senior residents	Improved skills and knowledge acquisition	Enhanced learning; Immediate feedback	Requires VR equipment; Learning curve
McKechnie et al. (2020) [33]	Various Surgical Procedures	VR simulation platforms accessible from home	Perspective	Surgical trainees during COVID-19	Continued training during lockdown	Remote accessibility; Mitigates disruption	Varying platform quality; Self-discipline required
Lohre et al. (2020) [34]	Complex Orthopedic Procedures	Immersive VR training	RCT	Senior surgical residents	Improved complex skill acquisition	Enhanced learning; Risk-free practice	Requires VR equipment; Technical setup
Cevallos et al. (2022) [35]	Pinning of SCFE	VR training with Osso VR	RCT	Medical students and residents	Improved performance metrics	Effective training tool; Potentially more effective than traditional methods	Small sample size; Pilot study
Munawar et al. (2024) [36]	Skull-Base Surgery	Fully immersive VR with haptic feedback	Experimental study	Surgical residents	Improved spatial understanding and skills	Realistic simulation; Haptic feedback	Technical complexity; Equipment required

sensations, allowing trainees to feel the resistance and texture of virtual tissues.

B. AUGMENTED REALITY IN SURGICAL TRAINING

1) Overview

Augmented Reality (AR) overlays digital information onto the real world, enhancing the user's perception of reality. In surgical training, AR can project anatomical structures, procedural guides, or hazard warnings directly onto the surgical field or physical models. While AR holds promise for surgical education, studies are still emerging, and its effectiveness compared to traditional methods is being explored. Table 3 summarises key studies on AR in surgical training.

2) Analysis

Heinrich et al. [37] introduced the HoloPointer, an AR-based virtual pointer application for laparoscopic surgery training using the Microsoft HoloLens. Their study involved surgical trainees performing virtual cholecystectomies with and without the HoloPointer assistance. The results showed that using the HoloPointer significantly improved the economy of movement and reduced error rates without increasing procedure time. The trainees reported that the HoloPointer was helpful for identifying anatomical structures and following instructions. However, the study was limited by a small sample size and required the use of AR headsets, which may not be widely available.

McKnight et al. [38] conducted a review on how AR and VR technologies are translating surgical training into surgical technique. They highlighted various applications of AR in surgical education, emphasizing its role in enhancing learning experiences and surgical outcomes. The authors discussed interactive simulations and real-time guidance as key advantages of AR. However, they also pointed out challenges such as the need for high-quality hardware and software, and the importance of validating these tools through clinical studies.

Goh et al. [39] conducted a systematic review of AR and VR applications in knee arthroplasty training. They found that AR offers enhanced visualisation and interactive learning opportunities, potentially improving surgical precision and trainee engagement. However, they noted that there are limited clinical studies validating its effectiveness and emphasised the need for high-quality research to establish the benefits of AR in surgical education.

3) Pros and Cons

The advantages of using AR in surgical training include:

- **Enhanced Visualisation**: Provides real-time overlays of anatomical structures onto the physical world.
- **Interactive Learning**: Engages trainees with interactive and immersive content.
- **Real-Time Guidance**: Tools like HoloPointer offer immediate visual guidance during procedures.
- **Hands-Free Interaction**: AR systems can enable hands-free operation, allowing surgeons to maintain sterility.

The disadvantages and limitations of adopting AR in surgical training include:

TABLE 3: Summary of Studies on AR in Surgical Training

Reference	Surgical Application	Technology Used	Study Type	Participants	Outcomes	Pros	Cons
Heinrich et al. (2021) [37]	Laparoscopic Surgery Training	AR Pointer (HoloPointer) using Microsoft HoloLens	Experimental Study	Surgical trainees	Improved movement efficiency and error rates	Hands-free interaction; Enhanced guidance	Requires AR headset; Small sample size
McKnight et al. (2020) [38]	Various Surgical Procedures	AR and VR technologies	Review	N/A	AR enhances surgical training	Interactive simulations; Real-time guidance	Need for high-quality hardware; Limited validation
Goh et al. (2021) [39]	Knee Arthroplasty	AR and VR simulation	Systematic Review	N/A	AR shows potential in surgical simulation	Enhanced visualisation; Interactive learning	Limited clinical studies; Need for validation

- **Equipment Requirements**: Requires AR headsets like Microsoft HoloLens, which may not be widely available.
- **Technical Limitations**: Issues such as alignment accuracy and system complexity can hinder the AR experience.
- **Limited Clinical Evidence**: Few studies have extensively validated the effectiveness of AR in surgical training.
- **High Costs**: Investment in advanced AR equipment and software can be substantial.

4) Sensing and Recording

In AR applications for surgical training, **sensing and recording** involve tracking the user's head movements, hand gestures, and the position of physical objects to accurately overlay digital information. Devices like the Microsoft HoloLens use built-in cameras and sensors to capture real-time data. For example, the HoloPointer uses head tracking to control a virtual pointer on the laparoscopic video screen, facilitating hands-free interaction [37].

5) Rendering and Playing

Rendering and playing in AR involve displaying digital content superimposed onto the real world through devices like AR glasses. The AR system processes sensor data to render 3D models, annotations, or guides that enhance the trainee's perception and interaction with the physical environment. In the case of the HoloPointer, virtual pointers and annotations are rendered onto the laparoscopic monitor, aiding in communication between trainer and trainee [37].

C. SUMMARY

The integration of VR and AR technologies in surgical training offers significant advantages over traditional methods by providing immersive, interactive, and realistic simulations. VR has been shown to enhance skill acquisition and confidence among trainees, although some studies suggest a need for further validation. AR holds promise for improving anatomical education, surgical precision, and training efficiency, as demonstrated by studies like Heinrich et al. [37] and McKnight et al. [38]. However, its effectiveness remains to be fully established due to limited clinical studies and small sample sizes. Ongoing research and technological advancements are essential to address these limitations and determine the optimal role of VR and AR in surgical education.

D. HAPTICS

The importance of haptic feedback in conventional and robot-assisted surgery training has been demonstrated in several works in the last two decades [40]–[42]. Most of them tested specific applications (e.g., laparoscopy [43]) where the interaction with the human body is mediated by a tool. The development and application of tactile simulators, while significantly advanced, remain in an early stage and are poised to play an increasingly critical role in medical training as technology continues to evolve. Tactile simulation has already demonstrated its effectiveness in training for minimally invasive procedures and those utilising tools as indirect tactile conduits, such as needles or drills. However, accurately simulating basic surgeries and procedures involving direct physical interaction with soft tissues remains a persistent challenge.

As training hours for surgical trainees decrease due to limited resources, and procedural complexity rises, simulation provides an essential solution to bridge the gap in hands-on experience. Haptic-enabled training, when implemented effectively, emerges as a valuable complement to traditional methods, enhancing skill acquisition, proficiency, and ultimately improving patient outcomes. While high costs limit the widespread adoption of haptic-enabled simulators compared to simpler, haptic-free alternatives, their potential value warrants closer examination. Drawing parallels to their successful use in fields like flight training and space exploration, further research is essential to determine whether haptics should become a standard feature in surgical simulators, balancing cost with clinical necessity.

In the rest of the section, we focus into the foundational components necessary for integrating haptics into surgical training. This involves a careful consideration of two critical elements: the sensors that capture and record tactile experiences, and the platforms designed to render these sensations accurately. Together, these components form the backbone of any haptic-enabled surgical training system, bridging the gap between simulation and real-world tactile interactions.

1) Sensing/recording

Pompilio et al. [44] proposed a wearable thimble that is capable of measuring the magnitude of the indentation force applied on the skin and the orientation of the finger pulp. In this way, the patient engages in a self-palpation task that entails indenting the skin by applying continuous pressure, all while wearing the sensing device. At the same time, the doctor supervises the palpation task and guides the patient through vocal instructions employing an audio-video communication channel, and can feel the force exerted by the patient on his own skin by wearing a force feedback device. Thus, by employing a suitable force-rendering device, the doctor can perceive a realistic 3 degrees of freedom (DoFs) force feedback during the tele-consultation. Moreover, the experimental findings demonstrate the efficacy of the wearable sensing device as a valuable tool for conducting remote palpation in home-based environments. Despite the relatively low technological complexity based piezoresistive-based force sensors offering a digital output for reading force over a specified full scale force span and temperature range, which limits the range of complete palpation techniques available to the doctor, this device provides fundamental information that proves instrumental in facilitating an initial assessment of potential patient injuries.

Dargahi et al. [45] have reported the fabrication of a piezoelectric tactile sensor that contains a teeth-shaped upper silicon layer, a patterned polyvinylidene fluoride (PVDF) film and an elastic substrate. Due to excellent linearity, wide bandwidth, high force sensitivity and minimal noise-to-signal ratio of the sensor, it was assembled with the laparoscopic grasper and tested theoretically and experimentally before using it for human tissues. In a nutshell, it was observed that the teeth-shaped touch sensor can be used to determine the magnitude of the applied force as well as the position of the applied force. The haptic feedback can be taken on the surgeon's finger or can be presented on a monitor in an analog/digital form.

Lisini Baldi et al. [46] proposed a hand-held sensing device equipped with a movable component to indent the tissue under examination and a force sensor (load cells) to measure the exerted force on the tissue's surface. The device features a rack-and-pinion coupling mechanism encased in a rigid structure, designed for secure handling by the patient.

2) Rendering/playing

Commercial haptic devices can be mainly classified in two categories: desktop grounded devices and wearable devices. The former are usually able to precisely render forces thanks to complex mechanical that often results in limited usable workspaces. Recently, wearable haptic interfaces have been designed with the aim of increasing the workspace and the possible interaction points [47], [48]. In Figure 2 possible types of haptic devices are reported.

Grounded Haptic Devices

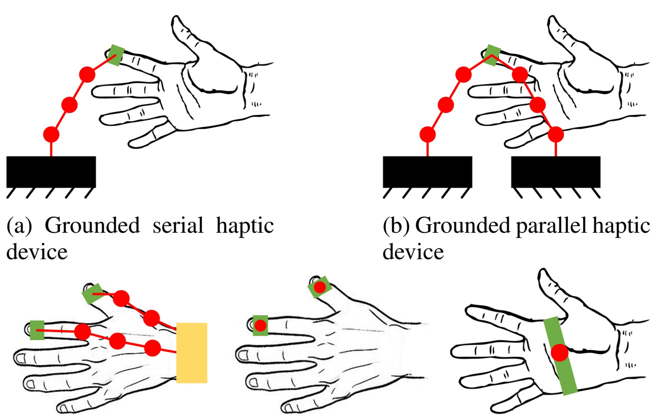
Grounded haptic devices are very accurate and able to provide a wide range of forces. However, they are often heavy and not portable or wearable. The grounded haptic devices include serial (Figure 2a) and parallel (Figure 2b) configurations. In [49], many different haptic devices are compared based on serial and parallel configurations.

The grounded serial haptic device has an open-chain mechanism. They have ample working space and high agility [50]. Nevertheless, they have low precision, weak force exertion ability, low payload-to-weight ratio, and high inertia [50].

On the other hand, the grounded parallel haptic device has a closed-chain mechanism. They have high stiffness, low inertia, high accuracy, high payload-to-weight ratio, and large force transmission bandwidth [50]. However, they have a small working space, singularity points, and low dexterity [50].

Wearable Haptic Devices

Wearable haptic interfaces can be broadly categorised into exoskeletons, which provide kinesthetic feedback, and thimbles or hand-worn devices, which deliver tactile feedback, see Figure 2. Exoskeletons simulate forces and motions by acting on the user's joints and muscles, enabling realistic interactions with virtual objects, such as replicating the resistance of surgical instruments. These devices can simulate large interaction force with high fidelity. However, they are still heavy and bulky. In contrast, thimble-like devices focus on stimulating the skin to convey surface textures and fine details through localised sensations like vibrations or pressure. While exoskeletons excel in simulating mechanical properties, thimble-like devices offer a lightweight and portable alternative, making them suitable for mobile VR/AR applications. These distinctions highlight the diverse capabilities of wearable haptics in enhancing VR/AR-based surgical



(a) Grounded serial haptic device
(b) Grounded parallel haptic device
(c) Exoskeletons
(d) Fingertip wearable haptic devices
(e) Palm wearable haptic devices

FIGURE 2: Types of haptic devices.

training.

Many types of actuators are adopte d in fingertip and palm wearable haptic devices to imitate the desired interaction force. Among them, vibration motors are the most common haptic actuators. In [51], a finger-worn, wireless haptic device is introduced. The module is stuck on the finger with a double-sided adhesive. A vibration motor is used to provide haptic feedback. In [52], a foldable haptic device worn on the user's fingernail is presented. With the foldable mechanism, the user can interact with the virtual and real objects at the same time in a mixed reality environment. Furthermore, the device can create three types of haptic effects: contact, high-frequency textures, and low-frequency textures.

Parallel Haptic Devices

The parallel mechanism is also considered in some studies. In [53], a wearable haptic device based on three degrees of freedom fingertip cutaneous device is proposed. The device is designed in order to fit several sizes and shapes of fingertips. In [54], a haptic device for the cutaneous stimulus of a hand palm is presented. The device is driven by three motors and a parallel tendon-based mechanism. It can apply both normal and tangential forces. In addition, the end-effector can be easily changed to reproduce the contact with different surface curvatures.

V. DIRECTIONS/ROAD-MAP ON HOW TO BETTER INTEGRATE AR/VR/HAPTICS FOR MEDICAL TRAINING

In this section, our directions/road-map on how to better integrate AR/VR/haptics for medical training is presented. This perspective overview is based on the research project titled "Beyond the Classroom: Virtual Reality, Augmented Reality and Haptics for Enhanced Surgical Training and Education (ImmersiveSurgicalEdu)" [1], funded by the European Union through the Erasmus+ Program under Grant 2023-1-NO01-KA220-HED-000160462. The project includes the following partners: University of Agder, Norway; Kaunas University of Technology, Lithuania; University of Siena, Italy; and Lithuanian University of Health Sciences, Lithuania. The main goal of this research project is to design, build, and test a haptic-enabled immersive platform for surgical education. This platform will integrate cutting-edge VR and AR capabilities with wearable haptic devices, giving students a realistic and immersive learning experience.

Referring to Figure 3, the following road-map is proposed.

A. DEVELOPMENT OF COMPENDIUM ON APPLYING IMMERSIVE LEARNING PRACTICES FOR MEDICAL STUDY PROGRAMMES

The goal is to provide a comprehensive compendium outlining the best practices in immersive learning for medical surgery education programs. The compendium will give an overview of several immersive learning approaches that may be utilised to improve surgical education. To achieve this, the following stages are considered:

- Design of Compendium Template. The first stage entails developing a template for the compendium. The template will serve as a foundation for arranging information on the many immersive learning approaches featured in the compendium.
- Identification and Description of Immersive Learning Practices. In this stage, the project team will identify and characterise the immersive learning methods that are most successful in improving surgical education. To identify these practices, the team will interact with stakeholders and draw on current research.
- Digitalisation and Integration of Compendium into Platform. The selected immersive learning approaches will be assembled and integrated into a digital platform. Students, professors, and other stakeholders in the medical education industry will have access to this platform. The interface will be user-friendly in order to facilitate access to the compendium.
- Piloting. The compendium will be tested on a group of students and educators during the piloting stage. The pilot study feedback will be utilised to develop the compendium and make required changes.

Ultimately, the compendium will be a great resource for medical educators and students by laying out the finest immersive learning approaches that may be applied to improve surgical teaching. Based on feedback from stakeholders, the compendium will be continually updated and enhanced, ensuring that it stays a relevant and helpful resource for years to come.

B. DEVELOPMENT OF IMMERSIVE LEARNING SCENARIOS FOR THE SELECTED STUDY PROGRAMME

This task is concerned with creating immersive learning environments for the selected study program. The task includes a number of processes that will ensure the development of interesting and successful learning situations:

- Selection of tools and scenarios. The project team will investigate and choose relevant technologies and settings for use in developing immersive learning scenarios. The selection will be based on the requirements of the chosen study program and the learning goals that must be met.
- Scenarios framework design. The project team will create the framework for the immersive learning situations after the tools and scenarios have been chosen. The learning objectives, storyline, and interactive aspects that will be implemented into the scenarios will all be part of the framework. This stage will be accomplished in conjunction with the Lithuanian partner who will contribute technical and educational competence.
- Development of immersive learning objects for the selected modules. After the creation of the framework, the project team will create immersive learning objects for the selected modules. These items will be intended to be interactive and engaging, employing approaches such as gamification and simulation to enhance the learning experience. The objects will be developed in

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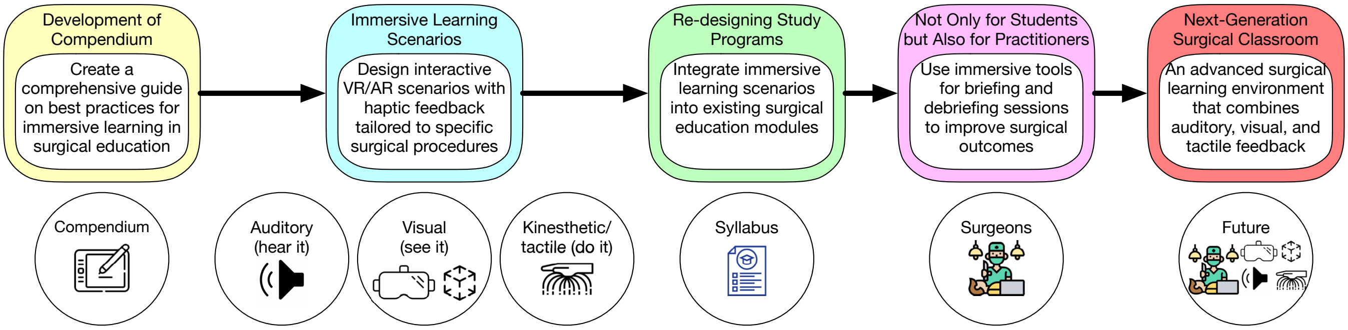

FIGURE 3: Directions/road-map on how to better integrate AR/VR/haptics for medical training.

consultation with the project partners, ensuring that they are customised to the requirements of the chosen study program.

- Piloting. The immersive learning scenarios and objects (i.e., human organs, wounds, ...) will be tested to verify that they satisfy the learning objectives and improve the learning experience. Students and instructors from the selected study program will participate in the pilots, providing input that will be utilised to develop the situations and objects.

C. RE-DESIGNING THE SELECTED STUDY PROGRAMME BY INTEGRATING THE DEVELOPED LEARNING SCENARIOS

This task focuses on rethinking the chosen study program through the incorporation of the immersive learning scenarios. This task is divided into the following stages:

- Selection of the modules for redesign. The team will pick the modules that will be changed to incorporate the immersive learning situations at this stage. The modules will be chosen based on their relevance to the learning objectives and the potential benefit of including immersive learning situations.
- Re-design study program modules with integration of immersive learning objects. The team will focus on redesigning the selected study program components in this stage. The emphasis will be on incorporating immersive learning objects into the selected study program's formal and non-formal education. The team will create a framework for integrating immersive learning scenarios into the study program, as well as recommendations for implementing the scenarios.
- Guidelines for the study program. The team will draft recommendations for implementing the new study program at this level. The recommendations will give a clear and comprehensive set of instructions for implementing immersive learning scenarios in both formal and non-formal education settings. The guidelines will also define the roles and responsibilities of the stakeholders who will be engaged in the implementation.
- Piloting. At this point, the team will undertake a pilot research to evaluate the efficacy of the modified study program. The pilot research will take place in Lithuania, and the team will collaborate closely with the stakeholders engaged in the program's execution to guarantee its success.

D. IMMERSIVE LEARNING FOR BRIEFING AND DEBRIEFING SESSIONS

Beyond the traditional application of immersive learning in student education, the developed platform can also be utilised for briefing and debriefing sessions among surgical teams. This additional application aims to enhance surgical preparedness and post-operative analysis:

- **Briefing Sessions Before Operations:** The platform can be used to conduct briefing sessions before surgeries, where colleagues can collaboratively review and simulate surgical procedures. This enables the team to discuss the operation's complexity, anticipate potential challenges, and align on the surgical strategy.
- **Debriefing Sessions:** Post-operative debriefing sessions can be conducted using the platform to analyse the surgical procedure, evaluate what went well, and identify areas for improvement. This process enhances awareness and contributes to continuous professional development.

Integrating immersive technologies into briefing and debriefing sessions fosters a culture of continuous learning and improvement, ultimately leading to better surgical outcomes and patient safety.

E. THE NEXT-GENERATION SURGICAL CLASSROOM

As part of our vision for advancing medical education, we propose a novel concept: the Next-Generation Surgical Classroom, as shown in Figure 4. The selected surgical procedure is performed and recorded by the doctor wearing a tactile/force recording interface. Successively, the same procedure is rendered to the student by using a wearable haptic interface. This classroom leverages the integration of AR, VR, and haptics to create an immersive, multi-modal learning environment that significantly enhances traditional educational methods. The Next-Generation Surgical Classroom not only aims at transforming how surgical education

FIGURE 4: Concept of the next-generation surgical classroom.: (a) the selected surgical procedure is performed and recorded by the doctor; (b) the same procedure is rendered to the student.

is delivered but also how students and professionals interact with patients, instructors, and each other.

This innovative classroom will be characterised by the following features:

- **Multi-modal Sensory Engagement:** Unlike traditional classrooms that rely primarily cadaver-based learning, the Next-Generation Surgical Classroom will engage students through a combination of auditory, visual, and tactile stimuli. This multi-modal approach is designed to cater to different learning styles and improve retention and comprehension of complex surgical procedures.
- **Interactive Simulations and Real-Time Feedback:** Students will interact with virtual patients and surgical environments, receiving real-time feedback on their actions. This interactive element allows for a hands-on learning experience that is crucial for developing the skills necessary for real-life surgical practice.
- **Collaborative Learning Environment:** The classroom will support collaboration between students, instructors, and even remote experts through networked AR/VR environments. This facilitates peer learning and allows for expert guidance during simulations, enhancing the educational experience.
- **Personalised Learning Pathways:** Each student's progress and performance can be tracked, enabling the creation of personalised learning pathways. This ensures that students can focus on areas where they need improvement while advancing more quickly through material they have mastered.

Table 4 compares the key aspects of the traditional classroom and the proposed Next-Generation Surgical Classroom, highlighting the differences in sensory engagement and educational impact.

The Next-Generation Surgical Classroom aims to address the limitations of traditional medical education by providing a more immersive, interactive, and personalised learning experience. By embracing advanced technologies such as AR, VR, and haptics, this classroom will better prepare students for the complexities of modern surgical practice, ultimately leading to improved patient outcomes.

TABLE 4: Comparison of Cadaver-Based Surgical Learning vs. Next-Generation Surgical Classroom

Aspect	Cadaver-Based Surgical Learning	Next-Generation Surgical Classroom
Sensory Engagement	Primarily tactile and visual; limited auditory input	Multi-modal: auditory, visual, and enhanced tactile feedback through haptics
Learning Method	Static and non-repeatable procedures on cadavers	Dynamic, repeatable simulations with real-time feedback
Ethical and Practical Constraints	Ethical concerns; limited availability of cadavers	No ethical constraints; unlimited, repeatable virtual scenarios
Student Interaction	Limited to observation and direct practice	Collaborative, networked learning with real-time peer interaction
Feedback Mechanism	Post-procedure feedback; no real-time correction	Immediate, real-time feedback and correction during simulations
Customisation	Uniform experience; difficulty in tailoring to individual needs	Highly customisable learning paths with adjustable difficulty levels
Accessibility	Requires physical presence; geographical and logistical limitations	Accessible remotely; global reach through AR/VR platforms
Tissue Variability	Limited, static tissue conditions	Simulated tissue variability for a broader range of learning scenarios

VI. CONCLUSION

This paper has explored the integration of Virtual Reality (VR), Augmented Reality (AR), and haptics as fundamental tools for modern surgical training. By offering immersive, interactive, and tactile learning experiences, these technologies address key limitations of traditional training methods, such as accessibility, repeatability, and objective skill assessment. Our structured review has highlighted both the strengths and challenges associated with these emerging modalities, providing insights into their potential to enhance surgical education.

Furthermore, we have outlined actionable guidelines for the effective implementation of VR, AR, and haptics in both academic and clinical settings. These recommendations aim to facilitate the adoption of these technologies in a way that maximises their educational impact, ensuring they complement existing training paradigms rather than merely supplement them.

Future research should focus on refining the fidelity of haptic feedback, improving system usability, and validating these technologies through clinical studies. By addressing these challenges, immersive technologies can bridge the gap between traditional cadaver-based learning and real-world surgical practice, ultimately contributing to safer and more effective surgical education.

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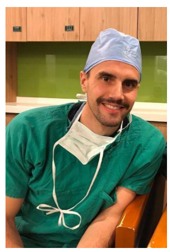

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