Tactical Medicine in Virtual Reality

Using VR to Improve Emergency Medical Preparedness

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Volodymyr Tretyak,
Matrikelnummer 01629766

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Betreuung: Univ.Prof. Dipl.-Ing. Dr.techn. Eduard Gröller,

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Volodymyr Tretyak

Eduard Gröller

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Volodymyr Tretyak,
Registration Number 01629766

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Advisor: Univ.Prof. Dipl.-Ing. Dr.techn. Eduard Gröller,

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Volodymyr Tretyak | Eduard Gröller

Technische Universität Wien
A-1040 Wien ▪ Karlsplatz 13 ▪ Tel. +43-1-58801-0 ▪ www.tuwien.at

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Wien, 7. April 2025

Volodymyr Tretyak

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Kurzfassung

Diese Masterarbeit dokumentiert die Konzeption, Umsetzung und Evaluation einer Virtual-Reality-Trainingssimulation für taktische Medizin. Die Anwendung wurde in Unity entwickelt und für das Meta Quest 3 Headset optimiert. Das System simuliert ein realitätsnahes Stressszenario auf Basis eines Messerangriffs und verwendet Handtracking zur intuitiven Interaktion. Im Mittelpunkt stehen Maßnahmen wie Triage, Blutungskontrolle sowie Kommunikation mit Verletzten und Umstehenden.

Zur Evaluation wurden zehn Personen mit Vorwissen in Erster Hilfe oder taktischer Medizin in eine qualitative Nutzerstudie einbezogen. Die Studie untersuchte drei Forschungsfragen: (1) Beeinflusst ein realitätsnahes Szenariodesign das Stressempfinden und die Immersion? (2) Wie unterscheiden sich Handtracking und Controller in Bezug auf Benutzerfreundlichkeit? (3) Wird VR als Ergänzung oder als Ersatz für herkömmliches Training wahrgenommen? Die thematische Analyse ergab, dass realistische Audio- und visuelle Reize die Immersion stärken, jedoch nicht zwangsläufig Stress erhöhen. Handtracking wurde als natürlicher empfunden, war jedoch technisch limitiert. Die Teilnehmenden bewerteten VR klar als sinnvolle Ergänzung, jedoch nicht als Ersatz für physisches Training. Die Ergebnisse unterstreichen das Potenzial von VR als skalierbare, immersive und sichere Trainingslösung im Bereich der Notfallmedizin.

Abstract

This thesis presents the design, implementation, and evaluation of a virtual reality (VR) training simulation for tactical medicine, developed using Unity and optimized for the Meta Quest 3 headset. The system recreates a high-stress scenario inspired by real-world knife attack incidents and integrates hand tracking for natural interaction. The training focuses on triage, bleeding control, and communication with injured patients and bystanders.

A qualitative user study involving ten participants with prior first aid or tactical medical experience was conducted to evaluate three research questions: (1) whether realistic scenario design affects perceived stress and immersion, (2) how different interaction methods (hand tracking vs. controllers) impact usability, and (3) whether users view VR as a complement or replacement for traditional training. Thematic analysis of the interviews revealed that realistic audio-visual cues increase immersion, but do not necessarily heighten stress. Hand tracking was perceived as more intuitive, though limited by technical constraints. Participants overwhelmingly saw VR as a valuable supplement to—but not a substitute for—physical training. The findings highlight VR's potential for scalable, immersive, and safe training solutions in emergency medicine.

Contents

CHAPTER 1

Introduction

1.1 Motivation and Background

In his seminal work *The Republic*, Plato presents the Allegory of the Cave as a philosophical metaphor for the process of enlightenment and the limitations of human perception [Pla68]. Within the allegory, individuals are depicted as prisoners confined to a cave, perceiving reality solely through the shadows cast on a wall by objects behind them—mere reflections of the true forms that remain unseen. This epistemological narrative underscores the tension between illusion and reality, appearance and truth. In contemporary discourse, the cave allegory has found renewed relevance in the context of virtual reality (VR), wherein users are similarly immersed in artificial environments that can convincingly replicate or abstract real-world experiences. Just as Plato's cave challenges the reliability of sensory knowledge, modern VR systems compel us to reconsider the boundaries between simulated experience and objective reality. This thesis explores virtual reality and examines its implications for perception, cognition, and experiential learning.

Virtual reality (VR) is a technology that fully immerses users in an artificial three-dimensional (3D) environment through the use of wearable devices like VR headsets [MFG17]. This immersive experience is achieved by artificially stimulating our senses, allowing users to perceive and interact with the virtual world as if it were real. VR involves four key components: a targeted experience designed by the creator, an organism (human or animal), engineered sensory input replacing natural stimuli, and the organism's unawareness of the artificial nature of the experience, which creates a convincing sense of presence [LaV23].

The project aims to demonstrate that VR can enhance practical skills in tactical medicine, improve decision-making under stress, and offer a more immersive training experience than traditional methods. Feedback from first responders will be used to refine the simulation and assess its impact on their preparedness and response capabilities.

Virtual reality is increasingly becoming an important area of research and is finding more and more applications. It is used in industry, training, education, simulations, and medicine. The analysis reveals a growing interest in the application of VR technology for educational purposes, particularly in skill development and training, and highlights the need for future research on the learning effectiveness of this technology [EYH24]. Universities are creating research groups focused on VR, and many companies—such as Meta, Apple, Microsoft, and others—are investing heavily in virtual reality technologies [DSZZ18], [SPR+20]. With the advancement of XR technologies, there has been a notable surge in research activity, accompanied by a significant rise in the number of publications [RMFW20]. Virtual reality devices are becoming increasingly popular among the general public, largely due to improved accessibility and availability. The number of VR devices sold has grown steadily each year. In the United States, the number of VR users increased from 22 million in 2017 to 66 million in 2023. Globally, it is estimated that there are approximately 171 million VR users [Zip23].

Training is one of the most important applications of virtual reality. Virtual reality allows to dive in in the immersive world, which might sometimes be very costly to recreate. Tactical medicine is also an important contribution here. In tactical medicine, traditional training methods such as dummies or mock scenarios are limited in their ability to replicate high-stress environments accurately. VR increases trainee engagement and concentration compared to traditional training [YSDJ23]. Recent developments in modular VR and MR-based training systems highlight the added value of immersive technologies across multiple dimensions of emergency preparedness. Modern systems combine mission planning, VR-based situational awareness, and MR-based first aid training to address challenges faced in civilian crisis response and peacekeeping operations. Especially in domains where decision-making under stress, communication, and patient care intersect, such frameworks offer scalable, repeatable, and realistic training environments that traditional settings cannot provide [BWSP+24].

One of the central aspects of virtual reality training is the interaction method. Interaction refers to the seamless and intuitive engagement between the user and the virtual environment. By providing responsive feedback, it aims to replicate the sensations and dynamics of real-world experiences, enhancing the sense of presence and immersion [LHT+19]. This thesis investigates different interaction methods and explores how realistic scenario design in VR—such as the recreation of high-stress events—affects trainee perception, immersion, and decision-making in the context of tactical medicine. In addition, it examines how users perceive VR's role alongside traditional training: whether they consider it a complementary tool or a potential substitute for hands-on simulations. These considerations form the basis of the research questions presented in the next section.

1.2 Research Questions

1. To what extent does the realistic recreation of real-world events affect trainees' perceived psychological stress and sense of immersion in virtual reality simulations?

2. What interaction method feels more intuitive and effective in tactical medicine training—natural hand tracking or traditional controller-based input?
3. To what extent do trainees perceive VR-based simulations as a valuable supplement or replacement to conventional tactical medicine training?

1.3 Contributions

The thesis project aims to demonstrate that virtual reality can enhance practical skills in tactical medicine, improve decision-making under stress, and offer a more immersive training experience than traditional methods. It also explores novel approaches to simulation. Feedback from trainees will be used to refine the simulation and evaluate its impact on preparedness and response capabilities. Specifically, the project investigates and compares interaction methods—such as hand tracking—in the context of virtual reality for tactical medicine training. It explores the recreation of real-world event scenarios for tactical medicine and assesses whether these environments make a measurable difference in trainee performance and perception. Furthermore, it examines user attitudes regarding whether VR-based training is seen as a supplement to, or replacement for, traditional first responder and tactical medical training.

1.4 Structure of the Thesis

This thesis is structured into seven chapters, each focusing on a distinct phase of the design, development, and evaluation of a virtual reality (VR) training system for tactical medicine. The chapters are organized to provide a logical progression from conceptual foundation to technical realization and empirical analysis.

Chapter 1: Introduction
The opening chapter establishes the motivation for exploring immersive technologies in high-stakes training environments, particularly in the context of tactical emergency care. It introduces the central research problem and outlines the relevance of VR as a tool for training under psychological and situational stress. The research questions are presented in alignment with practical and theoretical challenges. This chapter also clarifies the project scope, outlines the methodological approach, and briefly introduces the author's contributions.

Chapter 2: State of the Art
This chapter builds the theoretical foundation by reviewing existing literature on tactical medicine training, extended reality (XR) applications, and immersive learning environments. It surveys related projects, providing comparative insights into current training approaches. Further, it addresses human-computer interaction techniques within VR, the role of hand tracking, and the psychological implications of decision-making under pressure. The research questions are derived from gaps identified in the literature and practice.

Chapter 3: Methodology
The methodology chapter outlines the goals and functional requirements that guided the development of the training prototype. It details the iterative, User-Centered Design (UCD) process and specifies technical, experiential, and pedagogical criteria. The chapter introduces the qualitative study design used to assess user experience and training effectiveness, describing participant recruitment, study procedures, and the approach to thematic analysis.

Chapter 4: Implementation of the TacMedVR Prototype
This chapter presents the core technical realization of the training simulation. It describes the virtual training scenario, including narrative framing, spatial environment, medical tasks, and interaction flow. The system's architecture, asset creation pipeline, integration of Meta's XR SDK, and use of tools like Unity and Blender are discussed in detail. Special attention is given to the use of hand tracking, gesture-based interactions, and the challenges of simulating medical procedures such as hemorrhage control. Design decisions are justified with reference to both user needs and technological constraints.

Chapter 5: Evaluation
The evaluation chapter presents the results of the user study in relation to the three research questions. It reports on participant demographics, study conditions, and key themes that emerged during post-experience interviews. Aspects evaluated include perceived immersion, stress response, ease of interaction, realism of the scenario, and attitudes toward VR as a training tool. Qualitative insights are supplemented by screenshots and figures illustrating typical participant experiences.

Chapter 6: Discussion
This chapter interprets the findings of the user study in light of the initial hypotheses and research questions. It explores how the results support or challenge assumptions about the effectiveness of VR for stress-based medical training. The discussion addresses participant attitudes toward VR as a complementary or replacement training method, and evaluates the usability of natural hand tracking in complex medical scenarios. Identified limitations, such as interaction fidelity and communication barriers, are discussed as part of broader implications for future XR training systems.

Chapter 7: Conclusion and Future Work
The concluding chapter provides a summary of the thesis and highlights the contributions made to both the research community and practical training contexts. It reflects on the strengths and limitations of the prototype and the study, emphasizing the potential of VR in preparing first responders for emotionally and technically demanding situations. Suggestions for future work include are also elaborated.

Additional components of the thesis include a list of figures and tables, an appendix with screenshots and technical documentation, and a bibliography that covers both foundational and cutting-edge research in virtual reality, human-computer interaction, and medical simulation. A GitHub repository with source code and 3D assets is provided to support reproducibility and future development [Tre25].

CHAPTER 2

State of the art

2.1 Tactical Medicine

Tactical medicine, also referred to as Tactical Emergency Medical Support (TEMS), is a specialized field of medicine that operates at the intersection of emergency care and tactical operations. The basic principles of tactical medicine have existed for as long as there have been wars and battles, with historical accounts of treating the wounded dating back to the Spartan era. However, by the end of the 20th century, it became evident that a significant number of casualties were dying from preventable causes—primarily massive bleeding and airway compromise. This realization led to the development of standardized approaches such as TEMS [Mor13]. Although tactical medicine originated in military contexts—where medics provide care in active combat zones—it has increasingly been adapted for civilian use, including law enforcement, mass casualty incidents, and active shooter situations [CSC+11].

In contrast to traditional emergency medical services (EMS), tactical medicine emphasizes providing life-saving care in high-risk, dynamic environments before the scene has been fully secured. Practitioners must often balance medical intervention with situational awareness and threat mitigation. This includes procedures such as hemorrhage control, airway management, and casualty extraction, all of which must be executed under extreme stress and time pressure.

Tactical medicine in civilian use has expanded significantly in recent years, particularly in response to the rise in mass casualty incidents, including terrorist attacks and school shootings. Tactical Emergency Casualty Care (TECC), derived from the military's Tactical Combat Casualty Care (TCCC) guidelines, serves as a civilian framework for providing effective care in such scenarios. TECC protocols are widely adopted by police departments, fire services, and special response teams across the globe [SSS17].

Training for tactical medicine involves not only technical skills but also situational simulations that replicate the chaotic nature of real-life emergencies. The goal is to improve decision-making under stress, promote teamwork between medical and tactical units, and ultimately increase survival rates of both victims and responders [NL15].

As the scope of threats to public safety evolves, the role of tactical medicine continues to grow. Its principles are now being integrated into civilian emergency preparedness programs, school safety protocols, and even bystander intervention training, reflecting a broader societal shift toward proactive, life-saving measures in crisis situations.

2.2 Mass Causality Events

Mass casualty events (MCEs) are critical incidents in which the number of injured individuals overwhelms the immediate capacity of local emergency services and medical infrastructure. These events are a central focus of tactical medicine training, as they require rapid decision-making, triage under pressure, and efficient coordination between medical and tactical units.

Simulations and VR-based training scenarios often rely on mass casualty configurations to replicate the urgency and unpredictability of real-life emergencies. Scenarios can include a wide range of incidents such as terrorist attacks, large-scale shootings, school emergencies, explosions, chemical spills, and mass stabbing attacks [CR98]. These training environments are designed to expose trainees to high-stress conditions, complex environments, and the necessity of making life-saving decisions quickly and effectively.

While mass shootings and bombings have historically dominated public discourse around mass casualty events, in recent years, mass stabbing attacks have increased in frequency—particularly in German-speaking regions of Europe. More broadly, this trend is evident across the Western world. Over the past 15 years, the use of bladed weapons has risen significantly and, since 2014, has become one of the two primary weapons of choice for lone actors (alongside incendiary devices) [Pau20]. In Germany, there was an almost 10 percent increase in mass stabbing incidents in 2023 compared to 2022, with a total of 8,505 reported cases [Kni24]. In recent years, knife attacks and politically or ideologically motivated acts of violence have drawn increasing attention from both the media and security services. As discussed in a 2024 interview with Germany's Generalbundesanwalt Jens Rommel, the number of cases involving terrorism, espionage, and politically motivated crimes—including knife attacks—has significantly increased [DS24]. Rommel noted that such attacks, like those in Solingen or Mannheim, can occur at any time, underscoring the unpredictability of these threats and the importance of rapid emergency response preparedness. Recent reports from Germany's Federal Criminal Police Office (BKA) and leading sociologists have noted a marked increase in violent crimes, including bodily harm and armed assaults [Kol24]. In particular, the rate of serious bodily injuries has climbed to 183 per 100,000 inhabitants—a level not seen in decades. Experts also highlight a significant "dark field" (Dunkelfeld) of unreported cases, especially those involving domestic or sexual violence, making official crime statistics

Figure 2.1: Reported cases of violent crime involving stabbing weapons in Austria between 2010 and 2021. The upper graph shows the number of total reported incidents per year, while the lower graph specifically depicts homicides committed with stabbing weapons. Data source: Bundeskriminalamt, visualized by Breineder [SA23].

(PKS) only a partial reflection of societal developments. A similar trend is observable in Austria, as illustrated in the figure 2.1.

Some examples:

- In August 2024, a knife attack occurred at a festival in Solingen, North Rhine-Westphalia, Germany. Three people were killed and ten others injured during an outdoor event celebrating Solingen's 650th anniversary.
- On February 15, 2025, a 23-year-old man carried out a knife attack in Villach, Austria, killing a 14-year-old boy and injuring five others.

These cases highlight the need for medical personnel, first responders, and even civilians to be trained for non-shooting-related mass casualty events, which present different challenges in terms of injury patterns, scene management, and public panic.

In response to these developments, tactical medicine training programs are increasingly incorporating mass stabbing scenarios, adjusting triage protocols, and emphasizing hemorrhage control techniques, which are particularly critical in such events [Pau20]. Virtual reality provides a flexible and immersive medium to recreate these scenarios, offering dynamic environments where responders can develop both technical skills and psychological readiness.

This growing trend underscores the importance of adapting training to evolving threat landscapes and ensuring that simulations remain relevant to the most current forms of mass violence.

2.3 Extended Reality

At the beginning of this work, the concept of Virtual Reality (VR) is introduced. VR is defined as inducing targeted behavior in an organism by using artificial sensory stimulation, while the organism has little or no awareness of the interference [LaV23].

A broader conceptual framework for immersive technologies is referred to as *Extended Reality (XR)*, which encompasses Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) [VPF21]. While this work primarily focuses on VR, it is essential—particularly in the context of reviewing the state of the art—to also consider relevant research from adjacent domains such as AR and MR. To establish a clear understanding of these technologies, the following section defines the different forms of extended reality.

At this point, it is essential to understand and distinguish between the various types of extended realities. For the purposes of this work, the Reality–Virtuality Continuum proposed by Milgram and Kishino serves as a sufficient framework. This continuum is illustrated in Figure 2.2 [MK94].

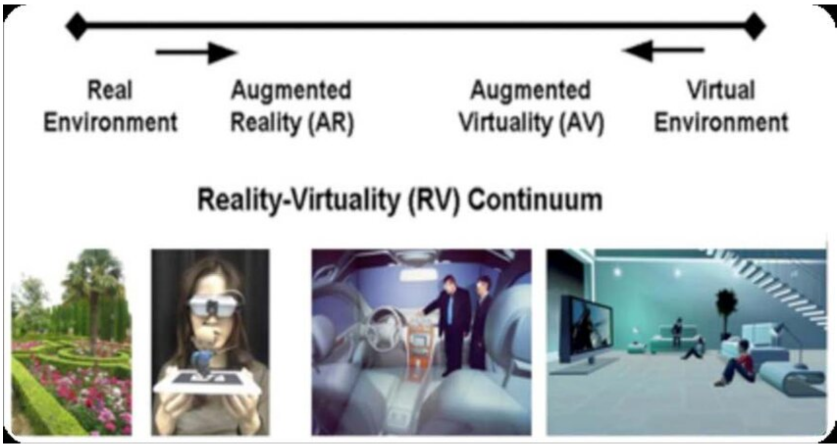


Figure 2.2: Reality-Virtuality Continuum with examples [KJK19]

- **Augmented Reality (AR)** refers to experiences where virtual elements are overlaid onto the real world, allowing users to perceive both real and digital content simultaneously.
- **Augmented Virtuality (AV)** describes systems where real-world elements are integrated into a predominantly virtual environment.

Figure 2.3: A group of professionals using mixed reality headsets to interact with a 3D digital twin [Mic20]

- **Virtual Reality (VR)**, also referred to as a virtual environment, is a fully immersive digital experience in which the real world is entirely replaced by a simulated one.

There are various approaches and new definitions that have emerged in recent years, particularly with the rise of Mixed Reality (MR)—the blending of real-world elements with virtual environments. While the exact definition may vary between institutions and researchers, MR is generally understood as a broad spectrum of experiences that merge physical and digital content. It goes beyond purely visual augmentation to incorporate interaction, immersion, and sensory integration (e.g., audio, haptics, geolocation), as illustrated in Figure 2.3 [SHN19]. Mixed Reality exists along the Reality–Virtuality Continuum, which spans from fully real to fully virtual environments and includes Augmented Reality (AR) and Augmented Virtuality (AV) as subtypes.

2.4 Applying Tactical Medicine in Extended Reality

First responder (FR) training is crucial, especially considering the increasing frequency of natural disasters [Eur16], terrorist attacks [Eur24], and other emergencies across Europe. Preparing for critical situations is essential, yet traditional non-digital simulation training methods are often costly and, in some cases, even unfeasible. For instance, involving children in live simulations is typically prohibited due to the risk of trauma, whereas such scenarios can safely be recreated in virtual reality. The same applies to simulating environmental effects like fire, rain, or hazardous conditions. For reasons of cost efficiency and flexibility, the use of extended reality (XR) technologies has proven to be an effective solution in this context [SRA+17].

A first responder is typically a trained professional—such as a police officer, firefighter, or emergency medical technician—who is among the first to arrive at the scene of an accident or crisis. While first responders come from various fields, they often face similar challenges: they must rapidly assess the situation to identify potential threats and environmental hazards, apply their knowledge of protocols and procedures, and take decisive action. In this regard, tactical medicine skills are valuable for all types of first responders.

Uhl et al. [URSF+23] extracted the main training goals that are frequently mentioned in the literature on FR training :

1. Knowledge of processes and rules,
2. Cognitive and emotional skills related to environmental threats,
3. Technical skills specific to the occupation (e.g., handling a weapon, treating patients),
4. Physical skills (e.g., endurance or fatigue during an operation), and
5. Communication skills (e.g., interacting with various stakeholders).

While modern technologies have the potential to support a wide range of training goals, not every form of extended reality (XR) is equally suited to address all of them. These core skills may be trained separately across different simulations or combined within a single scenario, provided the system is capable of effectively integrating multiple training objectives.

2.4.1 Selected XR Projects for Emergency Training

Several large-scale projects have demonstrated the successful application of XR technologies in the field of medical first aid. One notable example is **MED1stMR**—a European Union-funded initiative aimed at enhancing training for first responders through the use of Mixed Reality (MR). The project developed an innovative training framework that combines physical simulation equipment (such as manikins) with immersive MR environments to deliver highly realistic, scenario-based training. These simulations are designed to improve both the technical and emotional preparedness of first responders operating in high-stress, critical situations [ZGGSF+23]. By incorporating real-time physiological data, adaptive stress-inducing scenarios, and multi-user collaboration, MED1stMR provides a cutting-edge solution that bridges the gap between theoretical instruction and real-world emergency response. The project's results further confirmed that XR technologies—particularly MR—can be highly effective in medical training. Participants demonstrated increased situational awareness, faster decision-making, and improved

Figure 2.4: Medical first responders participating in a Mixed Reality training session during the MED1stMR project. Equipped with full-body tracking suits, VR headsets, and haptic gloves, participants engage in immersive simulations designed to enhance triage and coordination skills in high-stress scenarios [MED23].

retention of procedures compared to those trained using traditional methods. These findings underscore the potential of XR as a transformative tool in healthcare and emergency response education [HSFW23].

Despite these promising results, XR-based training systems are not without challenges. One of the primary concerns lies in the required resources—such as high-cost hardware and other specialized equipment—which may not always be accessible or maintainable for all institutions. Figure 2.4 illustrates the technical setup used during the MED1stMR project for Mixed Reality simulations.

Two other major projects aimed at first responder training worth highlighting are the **VERTIGO** project and **SHOTPROS** (see Figures 2.5, 2.6). The VERTIGO project was developed to support the training of European first responders in managing Chemical, Biological, Radiological, and Nuclear (CBRN) incidents. It underscores the broader applicability of XR technologies in preparing emergency personnel for diverse and high-risk scenarios [Eur21a]. It offers a novel and flexible virtual reality (VR) training system that allows realistic, multi-user training in large, immersive environments. The project emphasizes user presence, collaborative scenarios, and realistic interaction with mission-relevant virtual objects. A user evaluation conducted with experts from the Austrian Armed Forces showed high acceptance and confirmed the system's applicability for CBRN-crisis preparedness, with over 80% of participants strongly supporting its training potential [GPM+19].

Figure 2.5: Austrian military personnel training in the *VERTIGO* project using fully immersive VR equipment, including head-mounted displays, motion trackers, and backpack PCs. The project focuses on virtual CBRN defence scenarios. Image adapted from [GPM+19].

SHOTPROS, on the other hand, was initiated to enhance the decision-making and acting (DMA) capabilities of European police officers under stress and in high-risk situations. The project successfully demonstrated that a VR-based training framework can effectively prepare officers for complex, stressful environments—leading to improved performance and decision-making capabilities in real-world operations [HKK+22]. One of the key strengths of SHOTPROS was its human-centered design approach, which placed a strong emphasis on usability, realism, and psychological authenticity of training scenarios. The training framework allowed police officers to undergo dynamic and repeatable simulations, where both cognitive and emotional aspects of decision-making were tested under pressure.

The SHOTPROS project also contributed significantly to the broader discourse on collaborative virtual training. As highlighted in recent research [RUSF+22], the interplay between trainees and trainers in VR-supported environments introduces new didactic possibilities. Trainers in the SHOTPROS context could control and manipulate the virtual scenarios in real-time, switch between different roles (e.g., observer, role-player), and provide immediate or retrospective feedback. This greatly enhanced the instructional value of training, supporting better retention and behavioral transfer to real-world operations.

Moreover, the project explored how VR can foster team collaboration and situational

Figure 2.6: Police trainees participating in a virtual reality training scenario as part of the EU-funded *SHOTPROS* project, which explores decision-making and stress resilience under pressure. Image source: [SHO21].

awareness, including biometric monitoring (e.g., eye tracking, heart rate variability) for adaptive feedback. These innovations position SHOTPROS as a benchmark in VR-supported law enforcement training and highlight its potential transferability to other high-stakes domains like tactical medicine, military coordination, or civil protection. While these projects were not directly focused on medical training, they further validate the potential of XR technologies in the broader context of first responder preparedness.

Another notable initiative is the EPICSAVE project [Hoc19], which specifically targeted paramedic training through the use of virtual reality. The project aimed to enhance vocational education by integrating multi-user VR environments and serious game methodologies. It focused on simulating rare but critical medical emergencies—such as anaphylactic shock—that are difficult to cover adequately in traditional curricula due to their infrequent nature. Evaluation results from user studies indicated that the multi-user VR environment fostered high levels of presence and collaborative learning, highlighting its potential as an effective supplement to existing paramedic training programs [SLML18].

Further advantages of XR-based training include the simulation of psychological and cognitive stress, an essential component for first responder preparedness. Research by Schneeberger et al. [SPK+22] revealed that electrodermal activity (EDA)-based measurements of psychological stress showed no significant differences between real-world and VR conditions, suggesting that virtual environments can effectively replicate the stress levels encountered in live simulations . Additionally, cost-efficiency remains a major benefit: Mills et al. [MDH+19] estimated that mass casualty triage training for paramedic students is approximately 13 times more expensive in traditional live simulations compared to VR—while demonstrating comparable efficacy.

Taken together, these findings confirm that XR technologies represent an already established and evolving solution for training in tactical medicine, first aid, and first responder scenarios—continually advancing through innovative approaches and rigorous validation. Given these developments, it becomes increasingly relevant to explore whether such virtual reality applications are perceived merely as training supplements or if they may gradually evolve into partial replacements for traditional simulation formats. The question of acceptance and perceived effectiveness among practitioners remains open and worth investigating, particularly in light of technological progress and rising accessibility of VR platforms.

2.4.2 Limitations and Gaps in Current XR Training Systems

While recent years have seen an increasing number of XR-based projects aimed at medical training—such as EPICSAVE, MED1stMR, VIREM, and SIMXVR—several recurring limitations continue to shape the current state of the field. First, many existing systems exhibit a strong focus on highly specific scenarios, often centered around mass shootings or active shooter incidents. While these events are undeniably high-impact, this narrow thematic focus can reduce generalizability across other types of emergencies, such as knife attacks, blunt trauma, or domestic accidents. This gap highlights the importance of expanding XR training content to reflect a broader spectrum of real-world threats.

Moreover, most XR systems rely heavily on predefined, rigidly scripted scenarios. Although effective for procedural drills, such structures limit replayability and do not foster adaptive decision-making in dynamic environments. The lack of procedural variability or branching outcomes reduces ecological validity, making it difficult for trainees to apply what they have learned in more complex or evolving field conditions.

Another critical limitation is the absence of personalization or responsiveness to individual cognitive or emotional states. While research such as that by Pretolesi et al. [PZSF+23] introduces AI-supported adaptation in XR simulations, most existing platforms do not respond to user stress levels, performance, or learning pace. As a result, training intensity and complexity are not always aligned with individual readiness.

Additionally, full-scale XR systems often rely on expensive or cumbersome hardware—such as tracked manikins, external sensors, or dedicated simulation rooms—thus reducing accessibility and scalability. In contrast, the growing performance of standalone devices like Meta Quest 3 enables lighter-weight deployments suitable for decentralized and cost-efficient training environments.

Finally, natural communication and team interaction remain largely underdeveloped. Most existing systems offer limited or no support for voice input or collaborative multiplayer modes, which are critical for simulating the communication challenges faced by real-world medical teams. Some exceptions exist in military applications, but these are rarely accessible for civilian or educational use.

Addressing these gaps will be essential to unlocking the full potential of XR for tactical and emergency medicine education.Our **Tactical Medicine Virtual Reality (TacMedVR)** system, in its design and focus, attempts to respond to several of these limitations—offering more diverse scenarios, hand-tracked interaction, and a scalable standalone implementation.

2.5 Designing User Interactions in Virtual Reality

Designing effective user interactions is a critical component of developing immersive and impactful Virtual Reality (VR) applications. Interactions in VR go beyond traditional user interface concepts by requiring the integration of spatial awareness, natural movement, and sensory feedback [Kat21]. For domains such as medical training and first responder simulation, the choice and design of interaction techniques directly influence the training effectiveness and user experience.

In the context of Human-Computer Interaction (HCI), an interaction refers to the way in which a user communicates with a system to perform tasks or retrieve information [Don13]. This concept is expanded in VR to include full-body movements, gaze, gesture, and sometimes physiological feedback, reflecting the immersive nature of these environments. Interaction in VR is not only a means of control but a fundamental aspect of presence and engagement [SW97].

2.5.1 Types of Interaction in VR

Various interaction techniques have been developed for VR, categorized based on the input modalities and control strategies. [AA13] [JH01], [MLP16].These include:

- **Controller-based Interaction**: Users operate handheld devices with buttons, triggers, and joysticks to perform actions like grabbing, pointing, or navigating. This remains the most widely supported input method across commercial VR systems.
- **Hand Tracking and Gesture Recognition**: Using sensors or cameras, VR systems interpret users' hand positions and movements directly, allowing for more natural interaction. This approach supports object manipulation, medical procedures, or collaborative tasks.
- **Gaze-based Interaction**: Here, the system detects where the user is looking to highlight, select, or trigger elements. It is often used in scenarios requiring minimal hand interaction or for users with limited mobility.
- **Voice Commands**: Integrated voice recognition enables hands-free interaction, useful in complex workflows or sterile environments such as surgical simulations.

- **Haptic Feedback and Physical Interaction**: By integrating haptic devices or using physical props, users receive tactile responses to their actions, which increases realism and training fidelity.

2.5.2 Choosing the Right Interaction Technique

In high-stakes environments such as emergency medicine or disaster response, the choice of interaction technique must consider realism, efficiency, and cognitive load. Controller-based and hand-tracking interactions are predominant in these domains. For example, EPICSAVE [SLML18] utilized controller interactions to simulate teamwork between paramedics during anaphylactic shock treatment scenarios. However, MED1stMR [MED23] integrated Mixed Reality setups with hand tracking, allowing users to interact with physical manikins while immersed in a virtual scenario, thereby blending tactile and visual interaction.

A key consideration in such training applications is the balance between realism and system complexity. While full-body tracking or haptic suits can provide high levels of realism, they often involve higher costs and maintenance. However, it should be noted that in recent years, tracking solutions have become more accessible—for example, modern VR devices such as the Meta Quest 3 now include integrated hand tracking. Therefore, many systems opt for hand-tracking or hybrid controller-based approaches, which offer a practical compromise between immersion and feasibility [AA13].

Selecting the appropriate interaction model depends on several factors:

- **Task Complexity**: Fine motor tasks (e.g., administering an injection) may require precise hand tracking, while simple decision-making scenarios might only need gaze or voice input.
- **User Experience Level**: Novices may benefit from simplified or guided interaction methods, while experienced users may prefer natural and more flexible controls.
- **Training Goals**: If the goal is to simulate stress or realism, more immersive techniques like hand tracking and haptic feedback are preferred.
- **Hardware Availability**: Design must consider the target deployment environment. For example, portable systems might rely on inside-out hand tracking with devices like the Meta Quest Family.

2.5.3 Natural Hand Tracking and Its Benefits

Natural hand tracking, enabled by computer vision and depth-sensing technologies, offers users the ability to interact with virtual objects without external controllers. This method increases immersion and reduces the learning curve by mimicking real-world interaction metaphors [SMZ+16]. In training environments, hand tracking allows users to perform complex procedures with high fidelity, enhances collaboration by showing realistic hand gestures, and reduces equipment barriers. MED1stMR, for example, demonstrated that combining hand tracking with physiological data collection enabled more effective training under stress [HSFW23].

2.5.4 Implications for Training Design

Designing user interaction in VR is a multi-faceted process that requires balancing immersion, usability, and realism—particularly in first responder and medical training contexts. By selecting appropriate interaction techniques such as hand tracking, controller input, or hybrid systems, developers can create simulations that not only replicate real-world scenarios but also foster skill development and decision-making under stress. Future developments in sensor technology and AI-driven adaptation will further personalize and enhance these interaction concepts.

2.6 Psychological Foundations of Decision-Making

Designing an effective VR-based training simulation for tactical medicine requires a solid understanding of how individuals process information and make decisions, particularly if confronted with emotionally charged or uncertain situations. Psychological research has shown that emotions, cognitive biases, mental effort, and the interaction of intuitive and analytical thinking significantly shape human judgment. Recognizing these factors not only improves the design of more immersive and realistic VR environments, but also enhances the educational effectiveness of the simulation.

2.6.1 Emotion, Mood, and Processing Style

Empirical studies have demonstrated that negative emotions often trigger more systematic, detail-oriented cognitive processing. Luce, Bettman, and Payne [LBP97] observed that under negative emotional states, decision-making tends to become more extensive and attribute-based, as individuals focus more narrowly on specific aspects of available options. This implies that an emotionally evocative VR environment may help induce deeper information processing during training.

Tiedens and Linton [TL01] further differentiated among types of negative emotions and found that only uncertainty-related states—such as sadness or anxiety—lead to systematic message processing, while emotions like anger may instead encourage heuristic, overconfident judgments. These findings are particularly relevant in the context of emergency medicine training, where situational ambiguity and emotional stress are inherent to real-life conditions.

Raghunathan and Pham [RP99] showed that different affective states influence not only cognitive processing but also decision-making strategies. For instance, anxious individuals tend to choose low-risk, safe options, while sad individuals may pursue high-reward options despite associated risks. This has clear implications for how trainees in simulations might react to emotionally loaded scenarios. Depending on the emotional tone, users may adopt more conservative or aggressive treatment approaches—an insight useful for scenario balancing.

2.6.2 Affect as a Cognitive Signal and Learning Moderator

According to affect-as-information theory, emotional states function as contextual cues that influence which cognitive strategies are used [SS99]. People in a good mood tend to use top-down, heuristic processing, while those in a bad mood rely more on bottom-up, systematic evaluation. In a medical training context, this means that emotionally neutral simulations might not sufficiently engage deeper levels of cognition. Conversely, well-calibrated negative affect—such as background stressors or emotional dialogue—could increase learner attention to procedural detail.

In addition, Zajonc's [Zaj80] influential theory that "preferences need no inferences" underscores the pre-conscious nature of affective influence on judgment. Similarly, Bechara et al. [BDTD97] demonstrated through neuroscientific research that emotional responses are essential to decision-making; individuals with impaired affective signaling due to brain damage were less able to make effective choices in uncertain contexts. These insights validate the inclusion of emotional stimuli—such as time pressure, sound design, and social cues—to guide trainees' decision priorities and simulate real-world urgency.

2.6.3 Cognitive Load and Situational Complexity

The concept of cognitive load is central to both instructional design and situational decision-making. Cognitive load theory posits that learners have limited working memory capacity, and exceeding this can impair learning and decision accuracy [Swe98]. In a simulation like TacMedVR, the balance between instructional challenge and cognitive bandwidth must be carefully managed.

Tactical medicine scenarios inherently present high levels of intrinsic load due to their complexity. Extraneous load—caused by poor interface design or unclear task instructions—can interfere with the training effect. Therefore, the interface, feedback mechanisms, and task sequences must be optimized to support focused decision-making under load. For example, clearly visible prompts, responsive audio feedback, and intuitive object manipulation can help reduce unnecessary cognitive strain.

2.6.4 Dual-Process Thinking: *Thinking, Fast and Slow*

Kahneman's dual-process theory offers a compelling model for how users engage with simulations [Kah11]. The two systems are:

- **System 1**: Fast, automatic, emotion-driven. Useful for rapid triage or instinctual action.
- **System 2**: Slow, deliberate, analytical. Required for structured tasks like airway evaluation or protocol decision-making.

TacMedVR is designed to elicit and train the shift between these systems. For instance, exposure to simulated stress through chaotic environments encourages System 1 activation. However, as users gain familiarity and emotional regulation, they become more likely to engage System 2 processing—leading to deeper learning and better long-term retention of procedures.

The dual-process framework also supports progressive scenario design. Early scenarios may favor System 2 through calm, instructional guidance. Later levels can introduce noise, pressure, and ambiguity to train adaptive responses—teaching users to override intuition when necessary.

2.6.5 The Yerkes-Dodson Law and Stress Calibration

The Yerkes-Dodson law describes a bell-curve relationship between arousal (stress) and performance [YD08], [HS08]. Moderate stress levels can enhance cognitive performance by increasing alertness and attention. However, excessive stress impairs function, leading to decision paralysis or procedural errors.

In TacMedVR, this principle supports the staged introduction of stress-inducing elements—such as background audio, visual clutter, or distressed non-player characters (NPCs)—to simulate realistic pressure without overwhelming the trainee. Adaptive stress calibration (e.g., dynamically increasing urgency based on user performance) is a promising avenue for future work in personalized learning pathways.

2.6.6 The Conjunction Fallacy and Scenario Believability

Tversky and Kahneman's [TK83] *conjunction fallacy* shows how people overestimate the likelihood of vivid, detailed scenarios—even if these are statistically less probable. In VR simulations, this means that complex trauma scenarios involving multiple injuries may feel more "real" to users, even though simpler cases are more common in actual medical contexts.

While such narrative richness can increase immersion and engagement, it must be carefully moderated to avoid skewing learners' perception of typical clinical encounters. Overly dramatic cases may set unrealistic expectations or lead to miscalibrated prioritization in the field. Designers should balance emotional plausibility with pedagogical realism to preserve training accuracy.

2.6.7 Conclusion and Relevance to TacMedVR

By grounding scenario design in cognitive psychology, TacMedVR seeks to create not just technically accurate simulations, but cognitively realistic learning environments. Emotional triggers, stress-inducing cues, and decision complexity are not just cosmetic additions—they are essential variables shaping how users process, retain, and apply what they learn. Integrating theories of affect, attention, and decision-making into VR training design provides a scientific foundation for improving learning outcomes in high-stakes domains like tactical medicine.

CHAPTER 3

Methodology

3.1 Project Goals and Requirements

3.1.1 Overview

The aim of the project is to design and implement a virtual reality (VR) training simulation focused on tactical medical procedures under high-stress scenarios. Utilizing Unity as the development platform and targeting deployment on the Meta Quest 3 headset, the simulation is intended to support immersive and interactive learning for first responders, particularly in situations involving mass casualties or active threat environments.

3.1.2 Goals

The primary goals of the project are as follows:

- **Develop a realistic VR training environment** that replicates a scenario involving a mass casualty situation.
- **Simulate tactical medical procedures** including triage, bleeding control, airway management, and further treatment.
- **Train decision-making under pressure** through dynamic environmental stressors such as time constraints, audio distractions (e.g., screaming, music), and visual chaos.
- **Ensure user immersion and intuitive interaction** by implementing natural hand tracking and optimizing the experience for standalone devices like the Meta Quest 3.

- **Enable repeatable and adaptable training scenarios** that instructors can modify or reset easily, allowing for varied training outcomes and learner feedback.

3.1.3 Requirements

To translate the goals of the project into a working system, a number of requirements were identified across technical, experiential, and pedagogical dimensions. Technically, the application is required to operate natively on the Meta Quest 3 headset, functioning as a standalone experience without reliance on external hardware or tethering. Development must be carried out using Unity in combination with Meta's software development kits, ensuring compatibility and performance on the target platform. The system must support natural hand tracking as the primary interaction method, while also including fallback support for standard controller input. Additionally, the simulation should feature a dynamic logic framework capable of handling scripted events and branching outcomes, allowing for multiple variations of the same training scenario.

From a user experience standpoint, the simulation must allow trainees to move naturally within the environment, interact with virtual patients, and perform medical actions using intuitive hand gestures. A high level of immersion is to be achieved through the inclusion of realistic stress-inducing stimuli, such as loud background noises, visual chaos, and the perception of time pressure. Interface design should prioritize ease of use and low cognitive load, favoring in-world interactions over traditional UI elements like menus and buttons to preserve immersion and reduce distractions.

In terms of pedagogical design, the training content must be grounded in the Tactical Emergency Casualty Care – All Service Members (TECC ASM) guidelines [Com24]. This includes the implementation of core triage logic, such as identifying injuries and categorizing patients according to severity and required treatment. To enable post-session review and analysis, the system must also be capable of logging critical user actions, decision-making sequences, and response times, providing instructors with data to guide feedback and performance evaluation.

3.2 Research Questions and Hypotheses

The research questions for this thesis emerged from the practical challenges and opportunities encountered during the development of the training simulation. Throughout the iterative design process, it became clear that certain aspects—such as the emotional realism of simulated traumatic events, the intuitiveness of user interaction, and the perceived role of VR in professional training—played a key role in shaping the effectiveness and applicability of the system.

Although natural hand tracking has become increasingly available in modern standalone VR devices, there is still limited understanding of how far its capabilities can be pushed in demanding training contexts like tactical medicine. Additionally, while XR-based training systems have shown promising results, it remains an open question whether trainees see these tools as complementary or potentially substitutive to conventional methods.

The following research questions aim to explore these aspects in detail:

- **RQ1:** To what extent does the realistic recreation of real-world events affect trainees' perceived psychological stress and sense of immersion in virtual reality simulations?
- **RQ2:** What interaction method feels more intuitive and effective in tactical medicine training—natural hand tracking or traditional controller-based input?
- **RQ3:** To what extent do trainees perceive VR-based simulations as a valuable supplement or replacement to conventional tactical medicine training?

These questions are intended to evaluate both the experiential quality and functional performance of the simulation system, as well as its pedagogical value and user acceptance. The findings will help inform future XR-based training designs for high-stress emergency response environments.

Hypotheses

Based on existing literature and practical challenges observed during the early development phase, the following hypotheses are formulated:

- **H1:** Participants will report a higher sense of immersion and psychological engagement in simulations that recreate real-world events with high fidelity.

  This hypothesis is grounded in previous studies that found a positive correlation between scenario realism and immersion in VR training [SW97]. High-fidelity environments can also induce measurable stress responses similar to real-life conditions [SPK+22], which is particularly relevant in the context of tactical medicine.

- **H2:** Natural hand tracking will be perceived as more intuitive and effective than joystick-based interaction for performing medical tasks in VR.

  Prior work suggests that hand tracking offers a more natural and intuitive interface, especially for fine motor tasks such as object manipulation or tool usage [SMZ+16, SLML18]. However, its effectiveness can vary depending on implementation and hardware limitations—an aspect this study seeks to explore further.

3.3 User-Centered Design Approach

User-Centered Design (UCD) is a foundational methodology used throughout the development of the TacMedVR simulation. Rather than focusing solely on technical feasibility or aesthetic choices, UCD prioritizes the needs, limitations, and goals of the end users—in this case, first responders and trainees in tactical medicine. UCD is not a single-step procedure but an iterative, evolving process that emphasizes active user involvement from initial concept to final deployment. According to ISO 9241-210, UCD ensures usability and usefulness by integrating human factors and ergonomics principles throughout development [Don13].

UCD is particularly well-suited to high-stakes training systems such as tactical medical simulations. In such contexts, usability failures do not simply result in minor frustrations but can undermine learning outcomes or erode trust in the training tool. By keeping the user experience (UX) at the core, UCD ensures that interaction mechanisms are intuitive, scenarios are pedagogically relevant, and emotional and cognitive load is carefully managed.

To structure the iterative UCD process, the **Design Thinking** mode was adopted, which aligns closely with UCD in both philosophy and implementation. As illustrated in Figure 3.1, Design Thinking is a nonlinear, iterative methodology that emphasizes understanding user needs, defining problems, ideating solutions, prototyping, testing, and eventually implementing validated ideas [Bro09]. This human-centric model complements UCD by emphasizing creativity, rapid experimentation, and empathy throughout the design cycle.

Applying UCD to TacMedVR

The process began with the **Empathize** phase, during which training needs were assessed through literature reviews, analysis of similar systems (e.g., EPICSAVE, MED1stMR), and informal interviews with domain experts such as paramedics and military instructors. This phase aimed to understand not just what users do, but also the context in which they perform—emotional strain, time pressure, and physical limitations all played a role.

In the **Define** phase, collected insights were consolidated into design requirements. Key challenges were identified: how to simulate medical stressors without overwhelming users, how to support decision-making under pressure, and how to balance realism with usability. Personas and usage scenarios were drafted to guide subsequent design steps.

During the **Ideate** phase, multiple interaction and scenario concepts were generated. For instance, both gesture-based and controller-based interaction styles were considered. Ideas ranged from highly scripted trauma scenarios to more sandbox-style triage environments. While some were discarded, others informed early prototypes.

In the **Prototype** stage, the team developed both low-fidelity paper prototypes and high-fidelity Unity-based VR mockups. The focus was on building an environment that allowed intuitive medical interaction (e.g., applying a tourniquet or dragging a wounded soldier). The interface was tested on Meta Quest 3 using hand tracking to ensure realism and responsiveness.

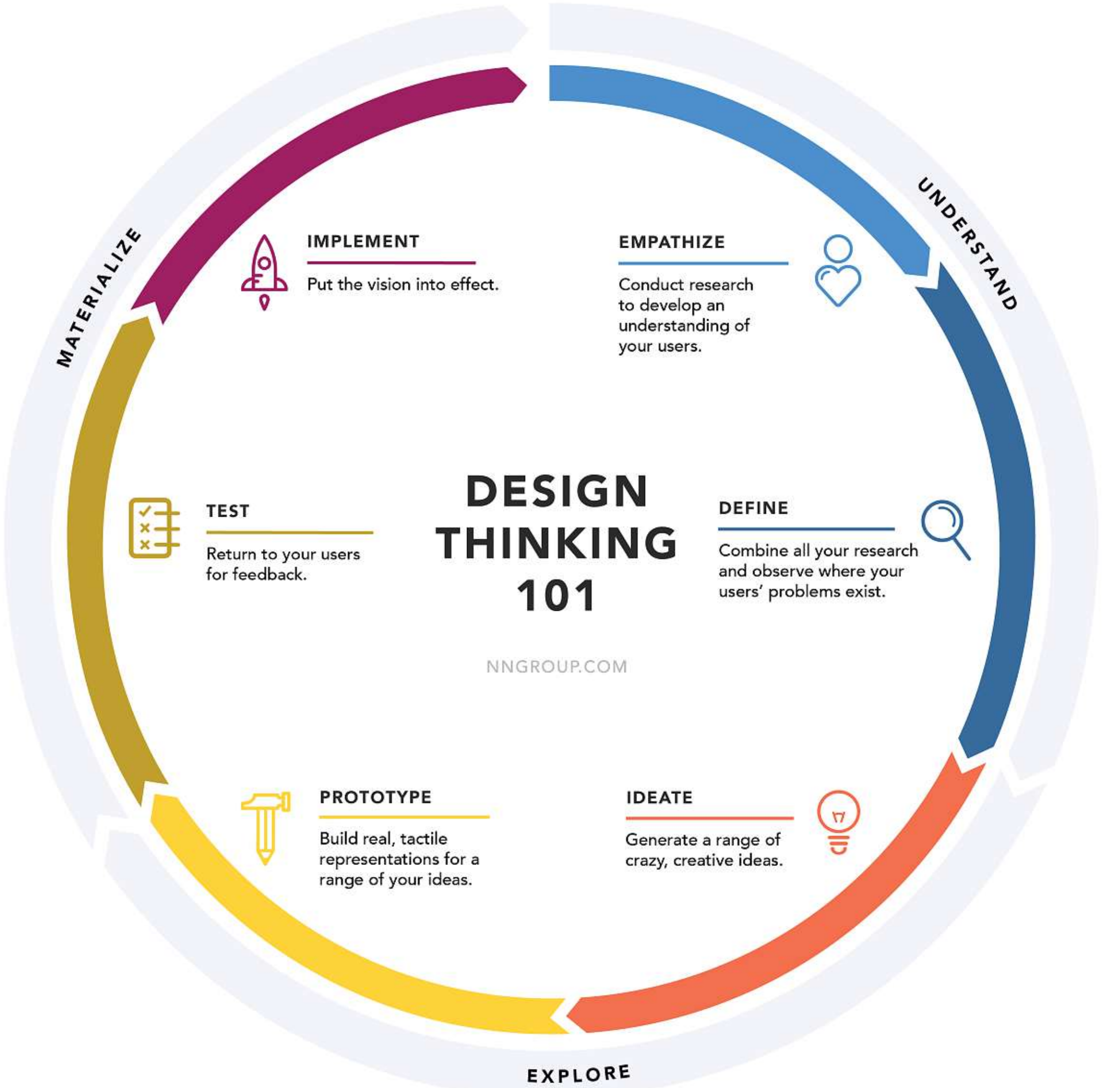


Figure 3.1: Design Thinking framework used to structure the UCD methodology [Nie16].

Next came the **Test** phase, in which early-stage feedback was gathered from test users, including simulation instructors and students. Usability issues—such as misinterpreted gestures or hard-to-read on-screen prompts—were identified and addressed.

Finally, in the **Implement** phase, validated components were integrated into a functioning prototype. Further refinements were made based on performance data and additional usability observations.

Why UCD Matters

By grounding development in UCD and structuring it around the Design Thinking framework, the TacMedVR system was designed not only to be functional, but also meaningful, usable, and emotionally appropriate. The iterative nature of UCD ensured that feedback loops informed every decision—from the way users interact with virtual patients, to how they perceive urgency and stress. This approach ultimately contributes to more effective training outcomes, greater system acceptance, and more confident and capable users.

3.4 Technology Stack Overview

The simulation was developed using **Unity**, a widely adopted game engine for immersive applications due to its flexibility, cross-platform capabilities, and extensive community support. The following tools and libraries were integrated into the development stack:

- **Unity (2022.3 LTS** [Uni23]) – Core development platform for 3D rendering, animation, physics, and scripting (C#).
- **Meta XR SDK for Unity** [Met24] – Provides essential VR functionalities including hand tracking, passthrough rendering, spatial anchors, and interaction systems specifically optimized for Meta Quest headsets.
- **Meta Quest 3** [Met23] – The primary testing and deployment platform, offering integrated hand tracking and passthrough AR capabilities for a portable, high-fidelity experience.
- **UMA 2 (Unity Multipurpose Avatar)** [UMA23] – Runtime character generation and customization system used for generating varied human avatars without the need for pre-modeled assets. Particularly useful for simulating different patients or first responders in training scenarios.
- **Blender** [Ble24] – 3D modeling tools for importing human models and assets, particularly for character design and animation.
- **Git** [The23] – Version control system used throughout the development process to manage source code and collaborative iterations.

This technology stack was chosen to allow for scalable development and ensure compatibility with future upgrades in XR hardware and software, especially within the Meta ecosystem. The tools were selected not only for performance and usability, but also for their support of realistic interaction design and rapid prototyping aligned with the UCD process.

User Study Design

To evaluate the research questions presented in this work, a single qualitative user study was designed to explore three central aspects: (1) the influence of realistic scenario reconstruction on perceived psychological stress and immersion, (2) the comparison of two interaction methods—hand tracking and controller-based input—in terms of intuitiveness and effectiveness for tactical medical training, and (3) the perceived role of VR in complementing or replacing traditional simulation-based education in tactical medicine.

A total of 10 participants were recruited, all with prior experience in tactical medicine or first aid. The study followed a two-stage process:

1. **Scenario Exposure (RQ1):** Five participants were provided with contextual information about the real-world incident upon which the simulation is based, while the remaining five engaged with the simulation without this background. Following their experience, semi-structured interviews were conducted to assess perceived psychological stress, realism, and immersion.
2. **Interaction Comparison (RQ2):** All participants experienced both interaction modes—hand tracking and traditional controllers—in randomized order to minimize order effects. Post-experience interviews were used to evaluate preferences, intuitiveness, and usability of the respective methods.

In addition to these two components, participants were also asked reflective questions related to **RQ3**: the potential of virtual reality to supplement or replace physical training methods. This included their perceptions of VR's suitability for use in actual training environments and its benefits or drawbacks when compared to traditional field simulations. Interview responses were transcribed and analyzed through thematic coding to identify key insights and recurring patterns relevant to all three research questions.

CHAPTER 4

Implementation of the TacMedVR Prototype

4.1 Observation of Real-World Tactical Medicine Training

To inform the design and development of the simulation environment, a real-world Tactical Emergency Casualty Care (TECC) provider course was observed. This course, held in Vienna from September 14 to September 15, 2024, is based on internationally recognized guidelines developed under the auspices of the Pre-Hospital Trauma Life Support (PHTLS) program [Nat23]. It specifically targets personnel from law enforcement, fire services, and emergency medical services, focusing on casualty care in high-threat environments.

The TECC course is structured into three operational phases:

1. **Care under Fire** – Immediate interventions while under active threat.
2. **Tactical Field Care** – Continued treatment once the threat is no longer immediate.
3. **Tactical Evacuation Care** – Medical care provided during transport from the scene.

The two-day course integrates theoretical instruction with extensive hands-on practical exercises (see Figures 4.1, 4.2). Key topics include hemorrhage control using tourniquets and hemostatic agents, airway management procedures (including cricothyrotomy), treatment of thoracic injuries, shock management strategies, administration of medications, and evacuation protocols. Upon successful completion of both written and practical evaluations, participants receive an internationally valid certification valid for four years.

The course was organized and led by experienced professionals in the field. **Michael Pauppill**, National Coordinator of TECC Austria, acted as one of the lead instructors and served as a key consultation partner throughout the development of this project. Mr. Pauppill is a paramedic with the Austrian Armed Forces and a certified trainer at the Sanitätszentrum Ost, holding a diploma in nursing. The medical oversight was provided by **Dr. Simon Martin Heinz**, Medical Director of TCCC/TECC Austria and Chief of Orthopedic Surgery at Klinikum Landsberg. Both experts contributed substantial insights into the realism and clinical accuracy of tactical emergency training content.

Permission was granted to attend the course in a non-participatory, observational capacity in order to better understand the instructional structure, tactical considerations, and specific workflows involved. Insights gained during this observation—particularly regarding environmental constraints, stress-inducing factors, and procedural decision-making—were directly integrated into the requirements analysis and design phases of the simulation. This observational study served as a foundational element in aligning the virtual training scenario with authentic practices and ensuring a high degree of realism and pedagogical value.

From a User-Centered Design (UCD) perspective, this observation was critical to the **Empathize** phase of the Design Thinking process. It allowed for a grounded, firsthand understanding of the physical and cognitive demands placed on trainees in real-world conditions. Observing the training scenarios, equipment usage, and instructor feedback provided valuable context for identifying pain points, usability requirements, and decision-making patterns under pressure. These insights were directly integrated into the requirements analysis and design phases of the simulation, ensuring that the virtual environment accurately reflects the operational realities of tactical medicine. By empathizing with the end users in their authentic training context, the simulation design could better address user needs, promote skill transfer, and enhance training outcomes.

4.2 Concept Development and Mockup Design

Throughout the duration of the project, regular consultations were held with a domain expert in tactical emergency medicine. These meetings, typically conducted after each development sprint, served as structured checkpoints to evaluate progress, validate design choices, and ensure the alignment of the simulation with realistic medical workflows and training goals.

This iterative expert involvement exemplifies the principles of **User-Centered Design (UCD)**—placing end-user needs and domain accuracy at the forefront of development. Rather than relying solely on theoretical assumptions, decisions were grounded in expert feedback, ensuring that the evolving prototype remained both usable and pedagogically sound.

Furthermore, from a design perspective, single-user scenarios allow for more focused evaluation of individual competencies—such as triage, situational awareness, and procedural accuracy—without introducing external variables caused by team dynamics. This isolation can be particularly valuable for early-stage learners, ensuring they develop a

Figure 4.1: Participants practicing airway management and hemorrhage control on a training dummy under simulated pressure.

Figure 4.2: A scenario simulating a confined-space casualty extraction with improvised stabilization techniques.

Scenes from the TECC (Tactical Emergency Casualty Care) Provider Course in Vienna. Participants undergo scenario-based training designed to prepare them for high-stress situations involving trauma care, evacuation, and teamwork in both open and constrained environments. Reference images were sourced from TECC Austria's official training documentation and media [TEC25].

foundational skill set before being exposed to collaborative complexity. As such, while multiplayer support remains a promising direction for future development, the single-user approach was selected to ensure technical stability, feasibility, and clear learning outcomes.

Figure 4.3: Initial mockup showing hands in a high-stress environment with nearby explosion effects.

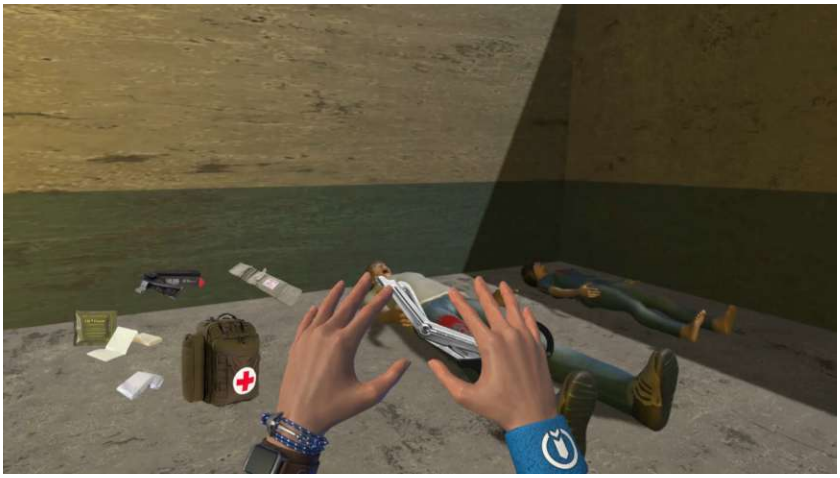


Figure 4.4: Follow-up mockup depicting medical tool interaction via hand tracking. The user is expected to apply scissors as part of the emergency treatment workflow.

During one such review session, early mockup scenes (see Figures 4.3, 4.4) were critically evaluated. The expert identified a major flaw in the depiction of fire and explosion effects in close proximity to the treatment area. It was noted that in real-world tactical medicine, such conditions would constitute an unacceptable risk and render the simulation scenario unrealistic. As a direct result of this feedback, the simulation environment was significantly revised—demonstrating how UCD principles guided design refinement based on real-world constraints.

4.2.1 Alternative Concept: Mixed Reality Implementation

During the early conceptual design phase, the idea of creating a **Mixed Reality (MR)** version of the simulation was explored as a potential alternative to fully immersive virtual reality. The envisioned scenario involved simulating a mass casualty incident occurring on the university campus, with the physical laboratory space serving as a designated *safe zone* for treating patients. Using the passthrough capabilities of the Meta Quest 3, trainees would have been able to see their physical surroundings while interacting with virtual elements—patients, equipment, and scenario cues—overlaid onto the real world.

In light of these considerations, the project refocused its efforts on optimizing the virtual reality experience to maximize presence, interaction fidelity, and emotional engagement in line with the project's learning objectives.

Figure 4.5: Early prototype of the Mixed Reality concept, showing passthrough view of the lab space with virtual medical elements overlaid. While offering navigational safety, this approach lacked the immersive fidelity required for stress-inducing emergency simulations.

Screenshots from this early prototype (see Figure 4.5) illustrate how the see-through mode could facilitate spatial awareness and reduce disorientation. The laboratory setting would serve as a familiar and safe environment, aiding navigation and grounding the

Figure 4.6: Scissors application in Mixed Reality: a 2D interface where the trainee performs virtual incisions in a real-world lab setting.

experience in physical space. The goal of this design was to blend real-world comfort with simulated urgency, creating a hybrid environment for controlled triage and treatment training. Trainees were able to interact with virtual medical tools—such as scissors, bandages, and airways—in the same way as in the full VR version, demonstrating that essential interactions could be preserved even in the MR context (see Figures 4.6, 4.7).

Despite these promising qualities, the MR approach was ultimately set aside in favor of a fully immersive VR simulation. Several factors informed this decision. First, the immersive nature of VR was deemed more effective for simulating the psychological stressors and environmental chaos typical of real-world emergencies. Full occlusion of the physical world allowed for more dramatic soundscapes, visual distractions, and scripted stress events—elements that are harder to convincingly stage in an MR context.

Second, expert feedback emphasized the importance of detachment from the everyday environment to improve focus and promote scenario realism. The visual presence of lab walls, furniture, or unrelated equipment in MR mode was considered distracting and counterproductive for deep situational immersion.

Finally, technical considerations—including lighting variations, passthrough latency, and spatial calibration inconsistencies—posed additional challenges for maintaining reliability across different real-world environments. Given the limited control over external physical

Figure 4.7: Tourniquet placement using Mixed Reality: combining real-world space with virtual medical overlays to simulate treatment application.

settings, MR was judged less suitable for delivering a consistent and repeatable training experience.

4.2.2 Final Scenario

Based on a recommendation from tactical medical expert Michael Pauppill, the design direction shifted toward a more appropriate and realistic threat: a knife or machete attack scenario. These types of incidents have become increasingly common in urban contexts and are considered high-priority by both emergency response trainers and law enforcement agencies. Moreover, such scenarios are currently underrepresented in virtual reality-based training platforms—**especially within the German-speaking domain**, where no machete-related VR scenarios are currently known to be in use.

In preparation for the scenario design, several real-world attacks were analyzed and discussed. One of the pivotal reference events was the knife attack in **Solingen, Germany (August 23, 2024)**, during the city's 650th-anniversary festival. An assailant attacked civilians in a crowded public space, resulting in multiple casualties. Notably, the performing DJ was instructed to continue playing music during the incident in order to *prevent mass panic* and maintain crowd control [New24]. This detail underscores the complexity of such emergency scenarios, where emergency responders must operate under psychological stress and amidst ongoing public activity.

Another case considered was the **Mondi Junction shopping mall stabbing** in South Africa (April 2024), where multiple victims were attacked in a public retail space. The scenario underscored the importance of rapid response in enclosed civilian areas with high foot traffic, limited visibility, and potential panic behavior.

A third relevant case was the **machete attack on a police station in Linz am Rhein**, Germany (June 2023), where an individual assaulted officers with a machete at the entrance of the station. This event provided insights into unexpected, high-threat assaults on secure facilities and reinforced the need for first responders to be prepared for edge-case scenarios in otherwise controlled environments.

To structure the medical response logic within the simulation, two widely used tactical frameworks were incorporated: the **3S-Regel** (see Table 4.1) and the **Ampelsystem** (see Table 4.2). These models help ensure that first responders assess environmental conditions before engaging in treatment and prioritize their own safety.

Table 4.1: 3S-Regel: Scene, Safety, Situation

Phase	**Description**
Scene	Refers to the type and nature of the deployment site. For example, industrial environments may include hazardous materials, and factors like time of day or weather can impact safety.
Safety	Focuses on ensuring the safety of responders. Potential dangers include aggressive individuals, hazardous substances, or unstable surroundings. Personal protection always takes precedence.
Situation	Involves the assessment of the current operational picture, including number of patients, injury severity, and prioritization of care. Determines how to allocate resources efficiently.

Table 4.2: Ampelsystem: Threat Level Classification

Zone	**Meaning**
Green	Safe zone. No active threats; medical interventions can proceed without restrictions.
Yellow	Unstable or unclear situation. Caution is required as safety status can rapidly change.
Red	Active danger present. Medical intervention is either unsafe or not feasible at this time.

The 3S model and Threat Level Classification are particularly relevant in the context of tactical medicine, where treatment priorities must adapt dynamically to the evolving threat landscape. Integrating these structured models into training not only enhances the realism of simulations, but also ensures alignment with contemporary tactical medical doctrine.

Early in the design discussions, the possibility of implementing a **multiplayer mode** was also considered. Since real-world tactical medicine is often performed by teams rather than individuals, a cooperative VR simulation could have increased realism and introduced valuable team communication challenges. However, for this prototype phase, it was decided to focus on a single-player experience due to several practical and pedagogical reasons.

First, implementing multiplayer support—especially in a VR context—introduces significant technical complexity, including synchronized networked interactions, latency handling, avatar consistency, and cross-device testing. These issues are particularly challenging to manage on standalone headsets such as the Meta Quest 3. Second, reliable testing and iteration of multiplayer systems would have required regular access to multiple participants and VR devices, which was not feasible within the scope of this thesis project.By incorporating real-world case studies, adopting frameworks such as the 3S-Regel and Ampelsystem, and addressing the current lack of VR-based machete training simulations, this concept development process underscores the value of **user-centered and context-aware design**. Each decision was anchored in authentic training doctrine and informed by expert critique, reinforcing the goal of producing an effective, immersive, and educationally sound training tool.

4.3 Functional Medical Scenario Components

4.3.1 Medical Equipment Setup and Modeling

After the scenario was defined in consultation with the domain expert, a realistic inventory of field medical equipment was required to populate the simulation. As a starting point, the domain expert, Michael Pauppil provided the official documentation of the **KTW PAX 2022 emergency medical backpack** (see Figure 4.8). This backpack layout, used by professional emergency services, includes categorized medical modules such as diagnostics, wound care, infusion sets, airway management tools, and resuscitation aids.

This document became a fundamental reference for the modeling of assets within the simulation. A number of objects were modeled directly in **Blender**, including commonly used tools such as syringes, and diagnostic instruments. In addition, high-quality 3D models of select items—such as tourniquets or oxygen masks—were sourced from open-access libraries if available, to accelerate development while maintaining visual fidelity. Within the virtual environment, trainees are able to grab, hold, and utilize these objects using hand tracking or controller-based interactions. This interactivity allows them to simulate realistic medical procedures—such as applying pressure to a wound, using bandages, or checking vitals—thus enhancing both engagement and learning outcomes.

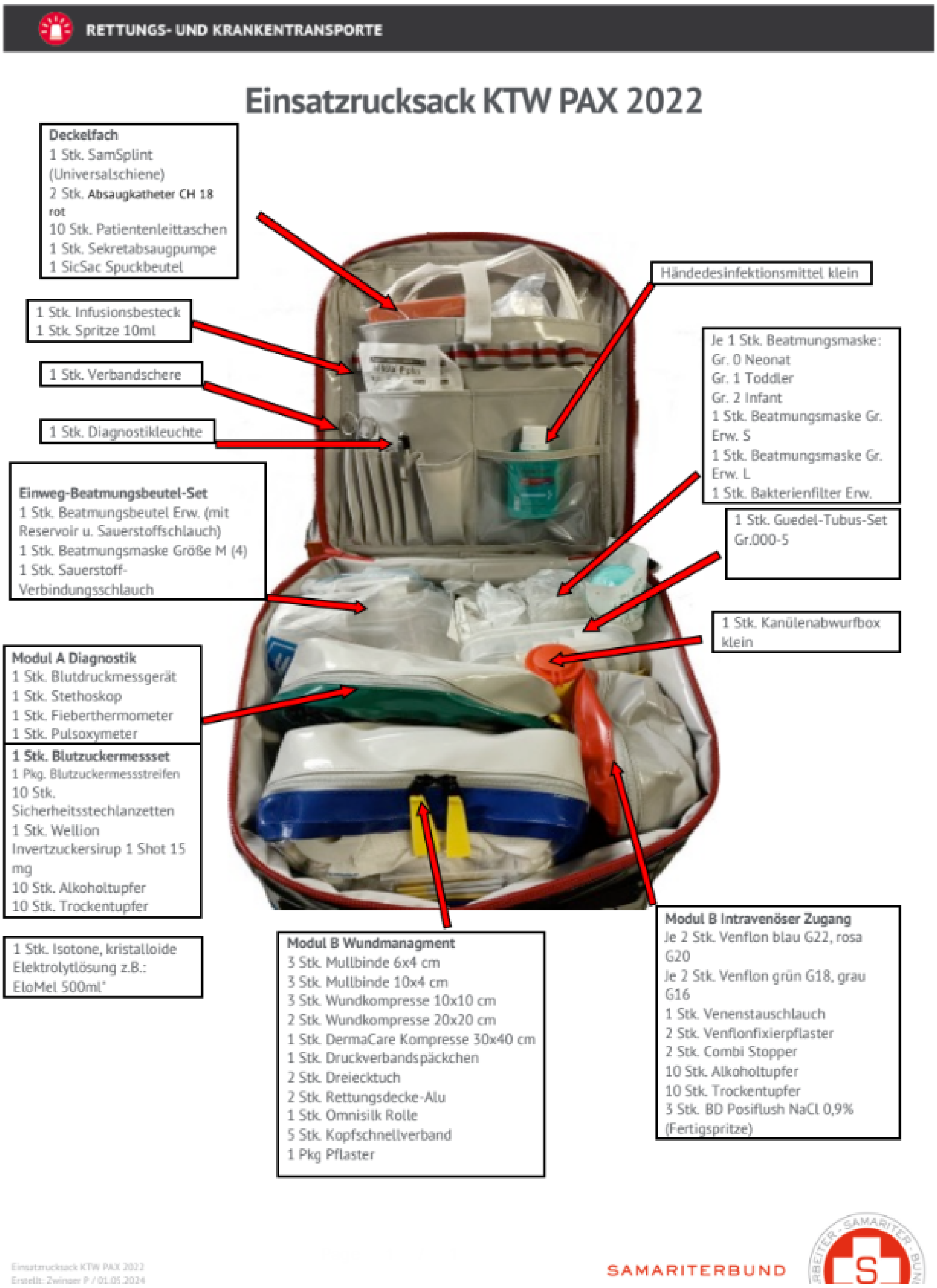


Figure 4.8: Overview of the KTW PAX 2022 emergency medical backpack provided by domain expert Michael Pauppil, showing modular organization of critical first-aid supplies.

Figure 4.9: Screenshot of the medical backpack as implemented in the virtual environment. The contents include: gloves, a tourniquet, trauma shears, bandages, elastic wrap, a combat gauze pack, adhesive plasters, a Cardiopulmonary Resuscitation mask (CPR) mask, wound dressing, emergency blanket, chest seal, Israeli bandage, medical tape, antiseptic spray, a flashlight, a teddy bear (for psychological support or pediatric simulation), and triage cards (green, yellow, red) based on the **MARCH assessment** (a structured approach to treating life-threatening injuries) and the **START triage protocol** (a system used to quickly prioritize patients based on the severity of their condition).

The resulting virtual backpack closely resembles its real-world counterpart in structure and content (see Figure 4.9). After an internal review with the domain expert, the in-game setup was approved as sufficiently accurate and usable for the intended training purposes.

4.3.2 Trauma Types

To design realistic treatment procedures in the simulation, it was essential to understand the clinical specifics of knife and machete-related injuries. Knife wounds may vary significantly in severity and treatment requirements depending on their type, depth, location, and whether major blood vessels or organs are affected.

Stab vs. Slash Wounds: Stab wounds are characterized by their deep and narrow penetration, potentially damaging internal organs and causing life-threatening internal bleeding. In contrast, slash wounds are typically superficial and affect a broader surface area but may still pose significant danger if major arteries or veins are severed [SS21].

Arterial vs. Non-Arterial Bleeding: Arterial bleeding involves bright red, pulsatile blood flow, reflecting its origin from high-pressure oxygenated vessels. This type of bleeding is more dangerous due to the volume and speed of blood loss. Venous or capillary bleeding is darker and oozes steadily; it is generally easier to control using direct pressure [RBC+10].

Perforating vs. Non-Perforating Trauma: Knife injuries are typically classified as non-perforating trauma, meaning they do not create exit wounds. In contrast, perforating trauma (e.g., gunshots) involves both entry and exit wounds, complicating internal injury assessment and treatment [Ame18].

Breathing Complications: Knife wounds to the chest or upper abdomen can compromise respiratory function. Injuries that puncture the thoracic cavity may lead to a sucking chest wound, where air is drawn into the pleural space, causing a collapsed lung (pneumothorax). In such cases, a chest seal or occlusive dressing should be applied to prevent further air intake and reestablish intrathoracic pressure. These injuries are time-critical and must be identified through signs such as labored breathing, asymmetrical chest movement, or audible sucking sounds during respiration.

Temperature Control and Hypothermia: Even in temperate environments, trauma patients are highly susceptible to hypothermia due to blood loss, immobility, and exposure. Hypothermia not only impairs blood clotting but also increases mortality risk. As a result, preventing further heat loss is a vital component of trauma care. Patients should be promptly covered with emergency blankets or insulating materials, and wet clothing should be removed if possible [RBC+10].

The trauma types chosen for TacMedVR directly map to critical skills emphasized in Tactical Emergency Casualty Care (TECC) training, particularly those under the "Care Under Fire" and "Tactical Field Care" phases. By focusing on junctional hemorrhages, abdominal trauma, and pediatric neck wounds, the prototype emphasizes time-sensitive interventions that require rapid prioritization and application of life-saving measures like tourniquets, wound packing, and airway monitoring.

4.3.3 Virtual Patient Profiles

Treatment Protocols: For most traumatic injuries, immediate bleeding control is paramount. According to European Resuscitation Council guidelines, direct pressure should be applied as the first step [Eur21b]. If unsuccessful, tourniquets or hemostatic dressings can be employed. Keeping the patient warm and monitoring for signs of hypovolemic shock are also standard components of field treatment.

To reflect this knowledge, three virtual patient profiles were created for the scenario, each representing a different injury pattern commonly associated with knife attacks. These patients are assigned triage categories according to urgency and survivability, as defined in the Table 4.3.

Table 4.3: Triage Categories for Patient Status

Category	Description
Red (Immediate)	Patient requires immediate intervention to survive (e.g., severe arterial bleeding). Will die without prompt treatment.
Yellow (Delayed)	Patient requires care soon, but is stable enough to wait. Can survive with delayed treatment.
Green (Minimal)	Patient is stable and can survive without immediate intervention. Minor injuries or psychological stress.

The selection of virtual patient profiles was guided by both medical relevance and scenario diversity. The inclusion of adult and pediatric patients with varying trauma types (e.g., abdominal puncture, limb hemorrhage, neck trauma) reflects common field injuries encountered by combat medics and emergency responders. This diversity ensures that trainees are exposed to a range of treatment protocols and anatomical considerations, which is critical for building adaptable, context-aware skills. Future iterations could incorporate less-represented patient types, such as elderly civilians or patients with comorbidities, to further increase realism and challenge cognitive load under stress.

Patient 1: Adult Male – Thigh Wound (Red)

- **Injury**: Deep stab wound to the thigh with suspected arterial bleeding.
- **Treatment Protocol**:
  - Apply a tourniquet above the wound to halt arterial flow. Record the application time on the skin.
  - Apply an Israeli bandage or gauze after bleeding is controlled.
  - Prevent hypothermia with an emergency blanket and monitor for signs of shock.
  - Administer mild analgesics such as paracetamol if needed.

Patient 2: Adult Female – Abdominal Puncture and Arm Lacerations (Yellow)

- **Injury**: Deep abdominal puncture and multiple arm lacerations. Breathing is labored with a sucking sound.

- **Treatment Protocol**:
  - Seal the abdominal wound with a chest seal or occlusive dressing.
  - Do not apply pressure to the abdomen; monitor breathing and use a nasopharyngeal airway if necessary.
  - Control arm bleeding with gauze and bandages.
  - If semi-conscious, place patient in the recovery position.
  - Continuously assess and prepare for evacuation.

Patient 3: Child – Neck Wound (No Airway Obstruction) (Green)

- **Injury**: Laceration to the neck with no airway or major vessel involvement.
- **Treatment Protocol**:
  - Control bleeding using an Israeli bandage.
  - Prevent hypothermia with an emergency blanket.
  - Provide psychological comfort with a stuffed animal.

Each profile was designed to train users in rapid triage and response, simulating a variety of stress-inducing, but realistic scenarios. Patients can be interacted with directly using hand tracking to apply tools and perform treatment procedures within the virtual environment.

4.4 Early Testing with Domain Expert

To validate the core interaction mechanics and assess the realism of the simulation, an early-stage usability evaluation was conducted with domain expert Michael Pauppill. The testing session took place in the university's VR laboratory, where the simulation was deployed on the Meta Quest 3 headset.

At the time of testing, the full environmental scene setup was not yet complete (see Figure 4.10) . However, the primary interactive components were implemented. Trainees could already interact with virtual patients using hand-tracked inputs, apply medical items such as tourniquets, bandages, gauze, and airway management tools.

4.4.1 Observations and Feedback

Feedback from the domain expert—an experienced paramedic and tactical trainer—was instrumental in validating the realism of both medical procedures and environmental stimuli. For example, the initial thigh wound treatment flow was found to lack intermediate steps like checking distal pulses, prompting an update to the interaction script. The expert also emphasized the importance of non-verbal cues (e.g., groaning, eye movement)

Figure 4.10: Screenshot from an early usability testing session with the domain expert. The scene shows two virtual patients in a prototype environment before final environmental elements—such as realistic lighting, textures, and props—were added. Despite the incomplete surroundings, key functionalities such as hand-tracked interaction with medical tools (e.g., tourniquet, scissors, airway devices) were already in place for testing core mechanics.

in pediatric patients, leading to the addition of subtle facial animations. This iterative process grounded the simulation in real-world practice and enhanced its instructional fidelity. During the session, several technical limitations were identified. One major issue was the limited granularity of the hand tracking system. Although the Meta Quest 3 provides accurate tracking for finger and palm movements, it lacks reliable tracking for wrist rotation, elbow orientation, and finer grasp dynamics. This limitation made it challenging to replicate certain medical procedures requiring precise hand rotations—for instance, tightening the windlass of a tourniquet. As a result, interactions that depend on torque or rotational forces felt imprecise or unintuitive.

4.4.2 Scenario Expansion Suggestion

Beyond the technical evaluation, the domain expert proposed a compelling narrative enhancement to increase realism and stress-inducing dynamics. He suggested introducing a non-injured bystander character to the scene—someone panicked or untrained, reacting emotionally to the incident by asking questions such as *"What's happening?"* or *"What can be done?"*. This character would serve both as an environmental distraction and an opportunity for the trainee to engage in verbal instruction or delegation (see Figure 4.11).

Figure 4.11: Interaction interface with a bystander character in the simulation. The trainee can choose from multiple dialogue options to address the bystander's behavior, such as instructing them to leave the area, remain calm, or assist in comforting the injured child. This mechanic enhances realism by simulating stress-inducing social dynamics and supporting non-medical communication skills.

The trainee could choose from limited contextual options to instruct the bystander:

- *"Hold the girl's hand."*
- *"Please remain quiet."*
- *"Leave the place."*

This addition not only reflects real-world psychological stressors, but also reinforces the importance of communication and leadership in chaotic emergency situations. The feature was subsequently implemented in the simulation, allowing the trainee to interact with the bystander through a set of predefined instructional commands. These interactions serve to simulate real-life team coordination under pressure and enhance the overall training experience.

Initially, the idea of including a non-responsive, irrecoverable patient—one that cannot be saved regardless of the interventions applied—was also considered. The goal was to introduce a challenging ethical dimension, forcing the trainee to prioritize limited resources.

However, the domain expert advised against this feature, noting that such a scenario is rarely presented in initial training contexts due to its psychological burden. Moreover, it could encourage counterproductive behavior, as trainees might spend excessive time attempting resuscitation, thereby disrupting the intended learning objectives and scenario flow. Consequently, the idea was discarded in favor of more pedagogically effective alternatives.

4.5 Final Integration and Adjustments

In the final development phase, ongoing iterations were carried out in close collaboration with the domain expert to ensure that the simulation fulfilled both instructional goals and technical feasibility. The resulting prototype integrates interactive components, spatial navigation, and realistic asset handling to reflect the demands of tactical medicine training.

To ensure users are properly introduced to the system and to support the main training scenario, several supporting scenes and systems were implemented. The following subsections describe the introductory tutorial, the integration of characters and dialogues, the navigation methods, the interactive medical equipment, and final tuning steps to enhance user experience. Together, these elements build the foundation for a coherent and immersive training simulation.

4.5.1 Introductory Tutorial Scene

To ease users into the simulation and reduce cognitive load during the main scenario, a dedicated tutorial scene was implemented. This scene serves as a sandbox-like environment where participants can become familiar with the basic mechanics of the system before engaging with the high-stress training scenario.

The tutorial introduces key interactions such as picking up and using medical equipment (e.g., scissors, tourniquets), object manipulation through hand tracking or controllers, and basic locomotion mechanics. Simple tasks—like placing a bandage on a dummy limb or toggling between teleportation and grab-based movement—help users build confidence and intuitive control.

The environment is visually minimal and quiet, designed to focus attention on interaction rather than narrative or environmental cues. Key prompts are provided through visual hints and object highlights to guide users without overwhelming them. This onboarding process was particularly helpful for users with little prior VR experience, as it reduced hesitation and increased performance in the main simulation.

Figures 4.12 and 4.13 provide an overview of the tutorial space, illustrating both the equipment layout and the instructional flow.

Figure 4.12: User interacting with virtual medical items using hand tracking.

4.5.2 Implemented Characters and Dialogue System

Three distinct patient avatars were implemented (see Figure 4.14a), each representing a unique injury pattern aligned with the defined scenario. These patients respond to treatment items and allow for various medical interventions.

Additionally, two non-injured characters were integrated:

- A police officer, who informs the trainee that the situation is under control and encourages focus on treating the wounded (see figure 4.15).
- A bystander NPC, whose presence introduces emotional and situational distraction. The trainee can choose from predefined dialogue options.

4.5.3 Locomotion and Scene Navigation

To accommodate varying room-scale setups and user preferences, two movement options were integrated:

- **Physical locomotion** using tracked movement within the VR play space.

Figure 4.13: Tutorial interface where the user initiates the training scenario by selecting one of the available options using hand tracking.

- **Teleportation**, activated either by hand gesture (in hand tracking mode) or via joystick/controller input (Figure 4.16).

Initially, an alternative locomotion concept was considered—*swing motion walking*, where players would simulate walking by swinging their arms in place. However, this method proved technically unfeasible due to limitations in optical hand tracking. When users move their hands behind their backs during the swing motion, the tracking cameras on the Meta Quest 3 lose visual contact with the hands. This leads to disconnection and reconnection cycles, breaking the illusion of continuous motion and creating usability issues.

The implemented teleportation mechanic allows users to move through the environment by pointing with their index finger and thumb extended in a pinch gesture. A target marker appears on the floor, and teleportation is triggered when the user performs a pinch-and-hold action for a short duration. This approach offers an intuitive and low-effort navigation method, particularly suitable for confined or safety-sensitive setups. This flexibility ensures comfort for users while maintaining accessibility and usability in constrained physical environments.

(a) Overview of the simulation scene before any treatment is applied.

(b) Scene after successful intervention by the trainee.

Figure 4.14: Progression of the training scenario from start to resolution.

Figure 4.15: Police officer character

4.5.4 Interactive Equipment and Customization

All medical equipment featured in the simulation—such as tourniquets, Israeli bandages, gauze rolls, trauma scissors, and more—was either self-modeled in Blender or sourced from optimized 3D asset libraries. These assets were then imported into Unity and configured to support dynamic interactivity within the simulation. To ensure flexibility and realism, all equipment was made compatible with the Unity Multipurpose Avatar (UMA) 2 system, a framework designed for creating fully customizable humanoid characters at both design time and runtime.

Using UMA, items such as clothing or medical tools could be added or removed from character models efficiently, enabling realistic simulations of trauma assessment and treatment. For example, trainees can remove clothing to inspect wounds more closely, allowing for accurate application of tourniquets or dressings. Alternatively, medical interventions like applying a tourniquet can also be performed over clothing, mimicking real-life decision-making if time or situational constraints prevent full exposure of injuries.

The integration of UMA not only allowed for mesh and texture merging, but also helped reduce draw calls and improve rendering performance—an important consideration for standalone VR devices like the Meta Quest 3. Moreover, this level of control provided

Figure 4.16: Teleportation tool using hand gesture

trainees with interactive scenarios that mirror the complexity of real-world fieldwork, from clothing management to wound accessibility. By simulating practical decisions, such as when to remove a piece of clothing or how to deal with obstructed injuries, the system aims to reinforce the procedural thinking required in tactical emergency care.

4.5.5 User Experience and Final Tuning

Through these iterative refinements, the simulation evolved into a highly immersive and context-sensitive training experience. Final adjustments were made to align user interaction flow, medical logic, and scenario pacing. The result is a realistic VR environment that enables trainees to practice both technical interventions and situational decision-making under pressure. Figures 4.14a and 4.14b illustrate the progression of the training scenario from start to resolution.

4.6 System Architecture and Technical Design

The simulation was implemented using Unity, following a modular architecture to ensure flexibility, maintainability, and scalability (see Figure 4.17). Each core functionality was

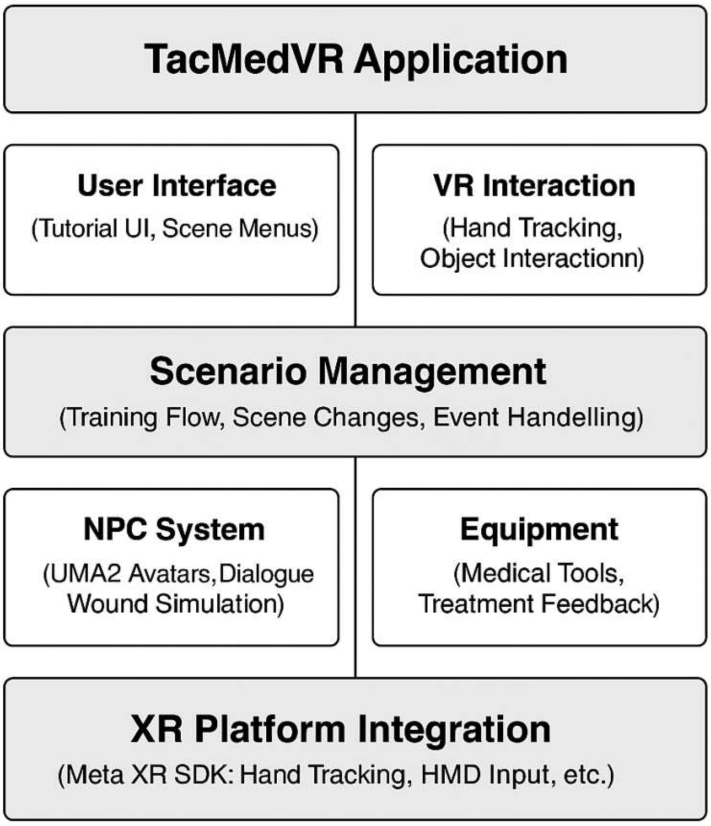


Figure 4.17: *High-level software architecture of the TacMedVR application. The system is structured into modular layers, with XR platform integration at the base, interaction and interface layers in the middle, and scenario management coordinating dynamic elements such as equipment systems and NPCs.*

encapsulated within separate modules, allowing for parallel development and straightforward debugging.

To ensure a robust and efficient development of TacMedVR, several key technical aspects were systematically addressed. The following subsections provide an overview of the core modules that structure the application, discuss deployment and performance optimization strategies, and explain critical design decisions such as audio implementation and scene management. Additionally, practical examples in the form of code snippets and project management practices are included to illustrate the applied workflows and ensure reproducibility.

4.6.1 Core Modules

- **Interaction Manager:** Handles input logic including hand tracking, controller input, and item manipulation.

- **Scenario Manager:** Controls the scene flow, event sequencing, and patient states depending on the user's actions.

- **Dialogue System:** Manages user interaction with NPCs such as bystanders and the police officer. It uses a simple branching logic based on predefined instructions.

- **Inventory System:** Keeps track of medical items and supports dynamic equipping and unequipping through UMA 2 integration.

- **Navigation Controller:** Provides locomotion via room-scale VR or teleportation (via controller or hand gesture).

- **UI/Feedback System:** Displays essential prompts, error handling messages, and status updates (e.g., item equipped, patient stabilized).

4.6.2 Deployment Modes and Optimization

The TacMedVR simulation was primarily developed for standalone use on the Meta Quest 3 headset, offering an untethered training experience that enhances realism and physical freedom. This configuration is particularly important in trauma scenarios, where users must be able to kneel, rotate, and move around virtual patients without restriction. Furthermore, running sessions without a tethered computer or external sensors simplifies deployment and increases accessibility in a variety of environments, including field exercises and mobile classrooms.

Despite its convenience, the standalone mode presents technical limitations. The Meta Quest 3, while significantly more powerful than earlier standalone devices, cannot match the computational capabilities of a high-end desktop PC. Consequently, several performance optimizations were required. These included compressing textures using ASTC (Adaptive Scalable Texture Compression), simplifying mesh complexity for secondary or decorative assets, limiting shader instructions, and pre-baking lighting to reduce real-time rendering demands. Such optimizations were essential to maintain stable frame rates and reduce latency, which are critical to both immersion and user comfort.

In parallel, the simulation was also configured to run in a PC-connected setup via Oculus Link. This option was primarily employed during internal testing sessions and research evaluations. Running the application on a desktop machine enabled higher graphical fidelity, more complex simulation logic, and the ability to monitor the simulation in real time through a connected display. Researchers could observe user actions directly, record data logs, and intervene quickly when issues were detected.

However, this tethered setup introduced its own drawbacks. The presence of a cable and the need for external tracking somewhat limited natural user movement, especially in scenarios involving floor-level interactions or sudden directional changes. Moreover, the potential for entanglement or tripping reduced the physical realism and safety of the training experience.

While both deployment modes were tested throughout the development cycle, the standalone configuration was ultimately chosen as the default platform for the final prototype. It provided the best balance between immersion, portability, and ease of deployment. Nevertheless, the desktop-connected mode remains an important option for structured research settings, formal usability testing, and environments where instructor oversight is necessary.

4.6.3 Performance Optimization Techniques

To ensure a smooth and immersive experience on both standalone and PC-connected VR configurations, several performance optimizations were implemented during development. These optimizations were critical for maintaining a high frame rate and minimizing motion sickness—especially important in high-stress medical simulations.

Unity's Profiler was used to monitor real-time resource usage. Texture compression was standardized using the ASTC format to reduce memory footprint without compromising visual clarity. For complex scenes, static lighting was pre-baked using baked global illumination (GI) to minimize dynamic light calculations during runtime. Shader complexity was reduced by merging materials and replacing transparent surfaces with opaque ones wherever possible.In terms of geometry, several 3D models—including medical equipment—were retopologized for efficient mesh rendering. Level of Detail (LOD) components were applied to background elements to reduce rendering load without sacrificing visual immersion. Special attention was paid to draw call batching and GPU instancing, which was especially impactful in optimizing the large variety of props and environment clutter in the scene.

The complete training scene in TacMedVR consisted of approximately 180,000 triangles at runtime. The environment meshes accounted for roughly 120,000 triangles, while character models generated with UMA2 contributed about 15,000 triangles each. Interactive equipment items, such as medical tools and props, typically ranged between 500 and 2,000 triangles per object. Physics interactions were also simplified. Non-essential rigidbodies were disabled, and collision layers were selectively applied to reduce unnecessary calculations. Texture resolutions were optimized to balance visual fidelity and memory usage, with most assets utilizing textures between 512×512 and 1024×1024 pixels. These measures ensured that the application consistently reached at least 90 FPS on the Meta Quest 3, even during complex interactions or audio playback (see Figure 4.18).

4.6.4 Audio Design and Implementation

Sound design played a central role in shaping the emotional tone and realism of the TacMedVR simulation. Given the scenario's focus on emergency medical care in a high-stress environment, the goal was to recreate an immersive soundscape that could evoke urgency and disorientation without overwhelming the user.

To achieve this, a combination of ambient sounds, character voices, and event-driven audio cues was integrated. Several environmental sound effects—such as distant sirens, muffled

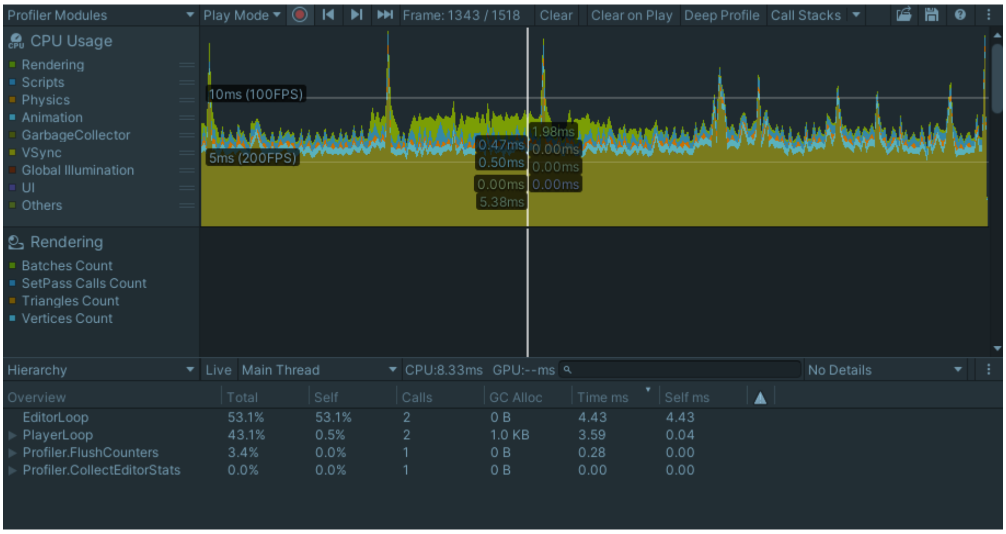


Figure 4.18: Unity Profiler output showing CPU usage during simulation runtime. The frame time averages around 8.33 ms, corresponding to more than 100 FPS, ensuring a smooth and responsive performance critical for VR applications.

crowd chatter, and mechanical background noise—were sourced from the open-source platform *freesound.org* [Fre24], ensuring a varied and authentic auditory backdrop. In addition to these library sounds, original recordings were captured manually using a portable microphone setup. This included sounds such as fabric movement, emergency bag zippers, and object handling, which were recorded in the university's lab space to match the simulated environment and actions more closely.

For spoken dialogue, including bystander reactions and ambient voice cues, the synthetic voice generation platform **ElevenLabs** [Ele24] was employed. This AI-based tool enabled the creation of high-quality, contextually appropriate voice lines that were realistic in tone and prosody. The flexibility and clarity of the ElevenLabs system proved particularly useful for simulating distressed speech, which was used to enhance the psychological intensity of the bystander character.

All sounds were spatialized in Unity using the XR Audio Toolkit and default spatial audio features, ensuring that sound cues were perceived as originating from specific sources in the 3D environment. Volume attenuation curves were customized to maintain clarity while preventing overwhelming input during critical interactions. Overall, the audio layer was not only functional but also pedagogical—prompting users through implicit cues (e.g., wheezing sounds for airway obstruction) and guiding focus during triage.

4.6.5 Scene Hierarchy and Prefabs

The Unity scene is organized with clean separation between static environment elements (e.g., buildings, terrain) and interactive objects (e.g., patients, NPCs, tools). Prefabs, which are reusable templates for GameObjects that store a preconfigured set of components and properties, are used extensively to represent reusable objects such as medical items or dialogue prompts. Each prefab includes:

- Mesh and collider
- Interaction script (e.g., `Grabbable.cs`)
- Animation triggers (if applicable)
- Audio cues (e.g., moaning, NPC voice lines)

4.6.6 Sample Code Snippet

The following script (see Listing 4.1) is responsible for applying a tourniquet to a virtual patient. It detects the interaction via colliders, updates the avatar using the UMA 2 library, and plays audio feedback.

This code snippet is included to illustrate the typical interaction logic between user actions, medical equipment, and dynamic avatar updates within the TacMedVR system.

Listing 4.1: Script for detecting tourniquet application and triggering feedback using the UMA2 system.

```
public class ApplyTourniquet : MonoBehaviour
{
    [SerializeField] private DynamicCharacterAvatar avatar;
    [SerializeField] private UMATextRecipe tourniquetUma;
    [SerializeField] private ParticleSystem bloodStream;

    private void OnTriggerEnter(Collider other)
    {
        if (other.gameObject.CompareTag("MedicalEquipment") && !TourniquetJeansA
        {
            var medicalEquipment = other.GetComponent<MedicalEquipment>();
            if (medicalEquipment?.type == "Tourniquet")
            {
                Tourniquet();
                medicalEquipment.applied = true;
                medicalEquipment.audioSource.Play();
            }
        }
    }
}
```

This modular setup ensures that updates can be implemented in isolation and that features such as new tools, characters, or interaction types can be added with minimal

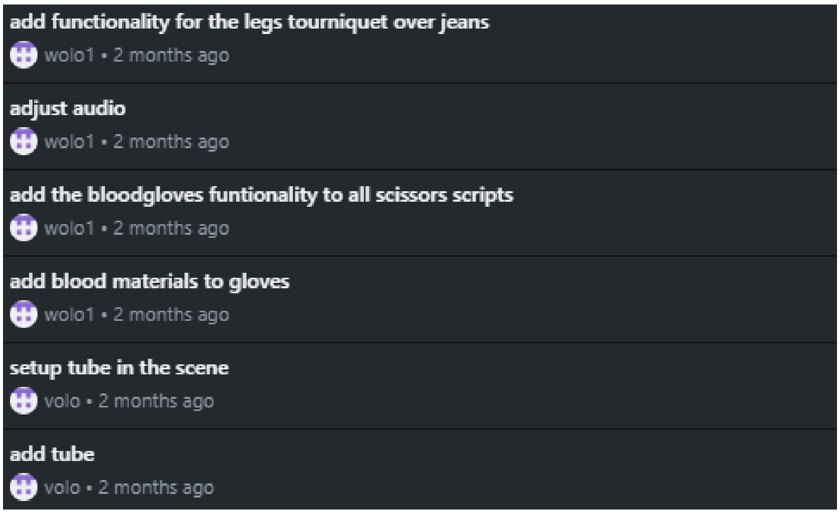


Figure 4.19: Excerpt from the Git history of the project, showing chronological commits with descriptive messages.

disruption to existing components. To scale the simulation with additional wearable items, new clothing assets must first be rigged to the UMA skeleton in Blender. Once imported, they can be integrated via UMA's recipe system and referenced in Unity scripts. This workflow makes it straightforward to expand the equipment library as new scenarios arise.

4.6.7 Version Control and Project Management

Throughout the development of the simulation, Git was used as the version control system to manage source code and track implementation progress. This approach facilitated structured development through commit histories, rollback capabilities, and incremental feature integration. The Git repository was organized into logical branches reflecting stages such as prototyping, interaction implementation, and final refinement.

Beyond its utility during the development phase, Git also lays the groundwork for future extension and collaboration. By maintaining a clear and well-documented history of changes, future developers or researchers can easily trace design decisions, revert to stable versions, or branch off to experiment with new features without disrupting the main codebase. Issues, pull requests, and milestones can be used to manage ongoing enhancements, track bugs, or integrate new modules like multiplayer support or AI-driven interaction. Hosted publicly on GitHub [Tre25], the repository serves as a foundation for transparent, collaborative development and invites contributions from the wider community—supporting the evolution of the simulation into a more robust training tool over time. Figure 4.19 shows a clean and well-documented Git history, highlighting the systematic approach taken during development.

CHAPTER 5

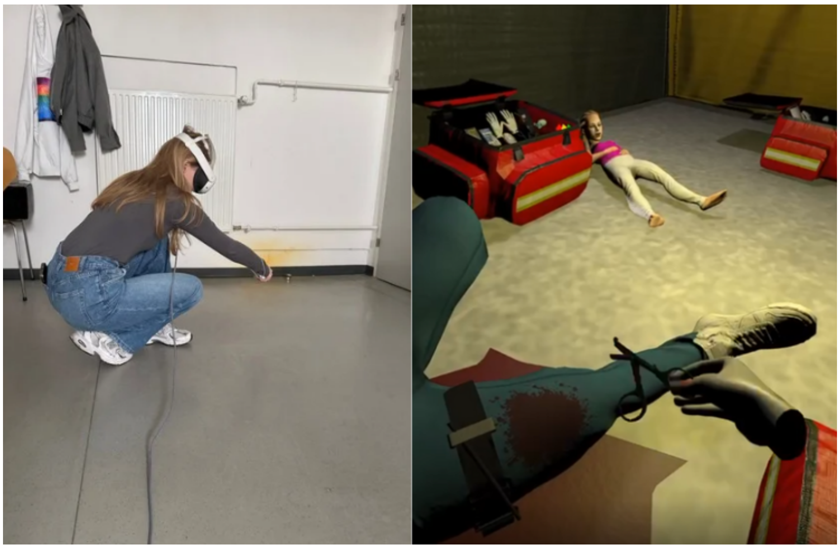
Evaluation

5.1 Procedure

The evaluation of the TacMedVR simulation was conducted through a user study designed to gather qualitative feedback on both the immersive experience and the interaction methods implemented in the prototype. Although an initial plan considered a quantitative evaluation approach—such as Likert scale questionnaires and performance metrics—this idea was ultimately set aside. Quantitative methods typically require a larger sample size to yield statistically meaningful results. Given the difficulty in recruiting participants with relevant medical training, a qualitative approach was chosen instead. This method allowed for in-depth exploration of subjective experience, decision-making processes, and emotional responses, providing rich insights despite a smaller sample size. The procedure was structured into two main phases: a hands-on VR training session followed by a semi-structured qualitative interview.

Each participant was first given a short briefing on the purpose of the study and an overview of the scenario. Basic demographic information was collected, including age, gender identity, and prior experience with virtual reality—ranging from no experience to regular use or professional familiarity. Afterward, participants were equipped with a Meta Quest 3 headset and instructed to complete the simulation involving three injured patients and one bystander. Depending on the assigned test condition, they first interacted with the environment either via natural hand tracking or standard VR controllers (see Figure 5.1). Interaction options included movement, medical actions such as applying a tourniquet or inspecting wounds, and issuing verbal instructions to the bystander using contextual dialogue prompts.

Following the simulation, participants took part in a semi-structured interview covering four key thematic areas. The first section addressed general experience and sense of immersion, with guiding questions such as: “Wie haben Sie die VR-Simulation insgesamt



(a) Participant performing the scenario using **VR controllers**. Controller input was used for navigation and interaction, offering higher precision but reduced naturalism.

(b) Participant performing the scenario using **hand tracking**. This mode allows for more natural gestures and enhanced realism in medical interactions.

Figure 5.1: Comparison of interaction methods used during TacMedVR simulation testing. Participants were randomly assigned to use either controllers or hand tracking to perform emergency procedures.

erlebt?” [translated: "How did you experience the VR simulation overall?"] or “Gab es etwas in der Simulation, das Sie überrascht oder unerwartet gefunden haben?” [translated: "Was there anything in the simulation that surprised or seemed unexpected to you?"]. Participants were also asked if they felt fully immersed and whether any moments made them feel lost or uncertain.

The second area focused on interaction methods. Participants reflected on how natural the hand tracking or joystick interaction felt, whether it influenced their performance, and how confident they would feel using such methods in a real-life emergency. For instance: “Gab es Aktionen, die frustrierend oder schwer auszuführen waren?” [translated: "Were there actions that were frustrating or difficult to perform?"] and “Hatten Sie das Gefühl, dass die Interaktionsmethode Ihre Leistung beeinträchtigt hat?” [translated: "Did you feel that the interaction method affected your performance?"].

The third theme explored stress factors and the role of audio elements. Participants were asked about their emotional response to the background noise, whether it impacted focus or added to the realism of the scenario. Typical prompts included: “Haben Sie sich gestresst gefühlt?” [translated: "Did you feel stressed?"] and “Wie haben die Hintergrundgeräusche Ihre Konzentration beeinflusst?” [translated: "How did the background noises affect your concentration?"].

Finally, participants were encouraged to share general impressions and suggestions for improvement. Questions included: “Glauben Sie, dass dieses VR-Training jemanden auf echte Notfälle vorbereiten kann?” [translated: "Do you think this VR training can prepare someone for real emergencies?"] and “Würden Sie dieses VR-Training anderen empfehlen?” [translated: "Would you recommend this VR training to others?"]. The interview also allowed space for open-ended feedback regarding realism, usability, or emotional engagement.

All interviews were audio recorded and transcribed verbatim. Thematic analysis was conducted using qualitative coding to identify recurring patterns across participants. This approach enabled the synthesis of insights related to immersion, training value, stress response, and user interface design—serving as a core foundation for the evaluation and refinement of the TacMedVR simulation. In addition to usability feedback, participants were also asked whether they could imagine the simulation being integrated into existing training programs within their professional environments.

5.2 Participants

A total of ten participants took part in the user study. All of them had prior experience in tactical medicine or first aid, ensuring that the feedback received was grounded in relevant domain knowledge. The participant group included individuals who had completed a voluntary social year in Austria, worked as first responders, or had comparable medical field experience.

Due to the realistic and potentially distressing nature of the simulation content, only individuals over the age of 18 were allowed to participate. All participants had undergone some form of emergency training and were familiar with the types of injuries portrayed in the scenario. The age range of the participants was between 20 and 30 years.

While all participants were medically trained, their familiarity with virtual reality varied significantly. Most had little previous experience with VR systems. This diversity in technical experience provided useful insights into the intuitiveness and accessibility of the interaction design.

Participants were recruited through two main channels: a professional network associated with the domain expert who had delivered TECC/first responder training courses, and a university Discord group, where individuals with voluntary service experience in emergency response roles were identified. Additionally, an attempt was made to recruit participants via thematic groups on platforms such as Facebook and Reddit, targeting communities focused on tactical medicine and emergency training. However, these efforts did not yield successful responses, possibly due to platform engagement limitations or strict moderation rules in those groups.

Each participant received a compensation of 20 EUR for their time, funded by the university to support research participation. The gender distribution was predominantly male, with nine male participants and one female participant. Although not representative of the general population, the demographic aligns with the current occupational distribution in tactical emergency roles.

5.3 Results

This section presents the findings from the qualitative user study, structured by key themes identified through thematic coding of participant interviews.

5.3.1 Immersion & Presence

Most participants reported a high degree of immersion, particularly if environmental and auditory cues aligned well with the simulated emergency. Many users expressed that the VR headset created a strong sense of presence and focus, as one participant explained:

> *„Man ist mit der Brille sofort sehr stark in der Situation drin und bekommt ein intensives Gefühl. Es war nicht extrem stressig, aber schon immersiv. Wenn es dunkler wäre, lauter, oder man mehr abgelenkt würde, wäre der Stressfaktor höher.“*
>
> *(Translation: With the headset, you are immediately very much inside the situation and get an intense feeling. It wasn't extremely stressful, but it was immersive. If it were darker, louder, or you were more distracted, the stress factor would be higher.)*

However, others found the environment too orderly and lacking in realism. One user noted:

> *„Es hatte eher Laborcharakter. Alles war schon vorbereitet. Ich glaube, das Szenario war: 'Wir sind Rettungsdienst und dürfen jetzt zum Patienten.' In dem Kontext hat das Material gepasst, aber normalerweise ist nicht alles sofort verfügbar.“*
>
> *(Translation: It felt more like a laboratory setting. Everything was already prepared. I think the scenario was: 'We are emergency services and are now allowed to go to the patient.' In that context, the material fit, but normally not everything is immediately available.)*

The absence of unpredictable events and visual distractions reduced the perceived urgency. Participants emphasized that more chaotic and emotionally charged settings, like flashing lights or crowd movement, could enhance immersion. Cable constraints and limited room-scale freedom slightly reduced the feeling of operational realism.

5.3.2 Hand Tracking & Controllers

Natural hand tracking was overwhelmingly preferred for its intuitive feel and relevance to real-world medical tasks. One participant said:

> *„Die Hände, auf jeden Fall – vor allem, wenn man es realitätsnah aufbauen will. Joysticks sind vielleicht etwas präziser, aber mit den Händen fühlt es sich echter an.“*
>
> *(Translation: Hands, definitely — especially if you want to make it realistic. Joysticks might be a bit more precise, but with your hands it feels more authentic.)*

Still, several limitations were noted. Technical inaccuracies—such as the inability to rotate the tourniquet realistically—were a source of mild frustration:

> *„Ich habe versucht, das Tourniquet zu drehen, aber das war schwer umzusetzen. In echt dreht man es mit der ganzen Hand, aber das wurde nicht sauber erkannt.“*
>
> *(Translation: I tried to turn the tourniquet, but it was hard to do. In reality, you turn it with your whole hand, but that wasn't properly recognized.)*

The stable recovery position was another recurring challenge:

> *„Die stabile Seitenlage war etwas schwierig – ich musste sie mehrmals probieren. Auch die Rettungsdecke war nicht so einfach.“*
>
> *(Translation: The stable recovery position was a bit difficult — I had to try it several times. Also, the rescue blanket wasn't that easy.)*

Despite minor flaws, participants appreciated the potential of hand-based input for learning spatial and procedural elements of trauma care. Suggestions included adding mechanics like realistic clothing removal, feedback when actions fail, and clearer affordances for tool use.

5.3.3 Stress

Stress responses varied widely. Some felt emotionally engaged, but not overwhelmed, while others thought the setting lacked urgency. A professional first responder noted:

> *„In meinem Profi Leben als Sanitäter auch nicht... mehr Lärm, Geschrei, Bewegung – wäre anders gewesen. Wenn z. B. ein Polizist durchs Bild rennt, erhöht das die Immersion.“*
>
> *(Translation: In my professional life as a paramedic — also no... more noise, screaming, movement — it would have been different. If, for example, a police officer runs through the scene, it increases immersion.)*

Others suggested that sound design could be a more active stressor:

> *„Die Musik hat mich eher rausgerissen. Sie hatte keinen Bezug zur Szene. Wenn man mehr Stress erzeugen will, braucht es mehr Umgebungsgeräusche, Dunkelheit, vielleicht Regen oder andere Störfaktoren.“*
>
> *(Translation: The music rather pulled me out. It had no connection to the scene. If you want to create more stress, you need more ambient noise, darkness, maybe rain or other disturbing factors.)*

The idea of gradual difficulty increase was mentioned as a solution:

> *„Man sollte mit einer einfachen Simulation anfangen, damit man sich an die Technik gewöhnt. Dann kann man langsam Stressfaktoren hinzufügen.“*
>
> *(Translation: You should start with a simple simulation to get used to the technology. Then you can gradually add stress factors.)*

5.3.4 Educational Value

Participants widely agreed on the simulation's training potential. Many saw it as a useful addition for preparing less experienced users:

> *„Man kann damit Abläufe üben, lernen, richtig zu priorisieren... auch Dinge wie Atemwege kontrollieren, Kleidung aufschneiden oder einen Patienten untersuchen."*
>
> *(Translation: You can practice procedures, learn to prioritize correctly... also things like checking airways, cutting clothing, or examining a patient.)*

Another participant added:

> *„Man müsste planen, wie viele Headsets man braucht und wie man den Ablauf organisiert. Aber es wäre eine sinnvolle Ergänzung."*
>
> *(Translation: You would have to plan how many headsets you need and how to organize the process. But it would be a meaningful addition.)*

It was also emphasized that such VR training should not replace physical exercises but rather complement them in blended learning settings. A few mentioned that even professional courses would benefit from integrating interactive digital tools, particularly for the repetition of core protocols and psychological preparation.

5.3.5 Technical Limitations

Technical issues were noted but did not significantly disrupt the overall experience. Key issues included inconsistent gesture recognition and lack of clear feedback during task completion:

> *„Es funktioniert grundsätzlich gut. Vielleicht wäre eine Textbox hilfreich, wenn man z. B. starke Blutungen nicht sofort erkennt."*
>
> *(Translation: It basically works well. Maybe a textbox would be helpful if, for example, you don't immediately recognize severe bleeding.)*

Another participant remarked on visual mismatches:

> *„Der Wendeltubus sah zu klein aus. Normalerweise entspricht er etwa der Länge zwischen Zeigefinger und Daumen – das hat hier nicht gepasst."*
>
> *(Translation: The oropharyngeal tube looked too small. Normally, it corresponds to the length between the index finger and thumb — that wasn't the case here.)*

Such details, although subtle, were seen as important for realism and teaching precision. Several users recommended adding visual cues, improved textures, and symptom-based feedback to enhance usability.

5.3.6 Summary

In summary, the qualitative findings are reflected both in Table 5.1 and Figure 5.2. Table 5.1 outlines key insights and representative quotes for each identified theme, while Figure 5.2 visualizes the frequency with which these themes were mentioned across all participant interviews. The distribution emphasizes the importance of interaction design, perceived immersion, and user feedback regarding stress and educational value.

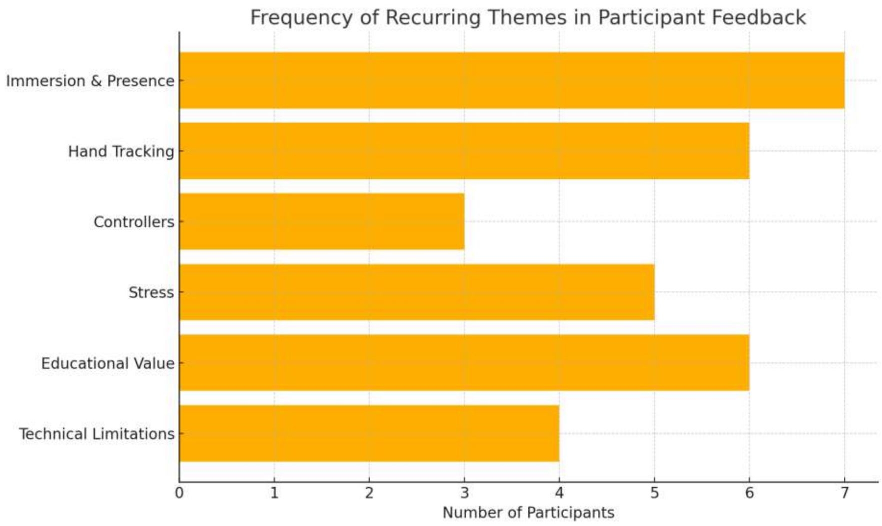


Figure 5.2: Frequency of recurring themes in participant feedback based on thematic coding (out of 10 participants).

Table 5.1: Summary of User Feedback by Thematic Category

Theme	**Representative Quote**	**Summary Insight**
Immersion & Presence	„Es fühlte sich an, als wäre ich wirklich dort – aber es war ein wenig zu sauber, wie ein Labor.“ (Translated: "It felt like I was really there—but it was a bit too clean, like a lab.")	Immersive, but environment needs more chaos or realism.
Hand Tracking & Controllers	„Handtracking fühlte sich sehr natürlich an, aber manchmal wurden meine Finger nicht erkannt.“ (Translated: "Hand tracking felt very natural, but sometimes my fingers weren't detected.")	Hand tracking is preferred over joysticks, but needs technical refinement.
Stress	„Ich habe keinen echten Stress gespürt, weil die Szene zu ruhig war.“ (Translated: "I didn't feel real stress because the scene was too calm.")	Users want more urgency and environmental stressors.
Educational Value	„Es ist eine großartige Ergänzung, besonders vor Feldübungen.“ (Translated: "It's a great supplement, especially before field exercises.")	TacMedVR is viewed as a valuable tool for pre-simulation training.
Technical Limitations	„Es hat meine Aktionen nicht immer klar erkannt.“ (Translated: "It didn't always register my actions clearly.")	Minor issues; more feedback and complexity requested.

CHAPTER 6

Discussion

6.1 Answering the Research Questions

This section discusses the results of the user study in relation to the research questions posed in the methodology chapter. Each subsection corresponds to one research question and reflects how the collected data contributes to answering it.

6.1.1 RQ1: To what extent does the realistic recreation of real-world events affect trainees' perceived psychological stress and sense of immersion in virtual reality simulations?

Based on participant responses, the connection between a simulation's factual realism (e.g., being based on an actual event) and perceived immersion or stress appears to be limited. While the scenario was inspired by a real knife attack, most users indicated that knowing this did not significantly influence their level of immersion or emotional engagement. Instead, immersion was more strongly linked to environmental design elements — such as 3D audio, spatial layout, and interaction fidelity.

Similarly, stress was more closely associated with the urgency of tasks, presence of ambient noise, and complexity of the patient interactions rather than with the narrative background. A few participants did express heightened awareness when told the scenario was grounded in reality, but this was not a widespread trend.

These findings partially contradict the initial hypothesis (H1), which expected that recreating real-world events with high fidelity would substantially enhance immersion and psychological engagement. Instead, practical sensory and interaction factors played a more decisive role in shaping user experience.

6.1.2 RQ2: What interaction method feels more intuitive and effective in tactical medicine training—natural hand tracking or traditional controller-based input?

Hand tracking was favored by the majority of participants for its intuitiveness and closer resemblance to real-world actions such as grabbing tools, applying tourniquets, or interacting with patients. It was especially praised for its relevance in training contexts that rely on manual dexterity. However, several limitations were noted — primarily concerning precision, detection reliability, and the physical constraints of hand gestures in a VR setup.

Conversely, joystick input was appreciated for controlled locomotion, particularly when users had difficulty maintaining accurate hand gestures. A few users preferred hybrid approaches depending on the task: hand tracking for object interaction, and controllers for navigation.

These results support the initial hypothesis (H2), which proposed that natural hand tracking would be perceived as more intuitive and effective for performing medical tasks in VR. While hand tracking was generally preferred, some minor technical limitations suggest opportunities for further optimization to maximize usability.

6.1.3 RQ3: To what extent do trainees perceive VR-based simulations as a valuable supplement or replacement to conventional tactical medicine training?

Participants widely agreed that the simulation has strong potential as a supplementary training tool. It was seen as an effective platform for learning medical protocols, recognizing injury patterns, and practicing verbal communication under pressure. Many respondents emphasized its suitability for onboarding new personnel or preparing lay responders before live training events.

However, nearly all participants stressed that VR simulations should not replace hands-on training with physical manikins or real-world drills. Instead, they envisioned the VR module as a bridge between theoretical instruction and full-scale simulation exercises. The ability to repeat scenarios, explore variations, and safely make mistakes was seen as particularly valuable. Thus, the simulation was validated as a useful addition to a blended learning approach in tactical medicine training.

6.2 Interpretation and Implications

The results of the qualitative user study provide several important insights into the effectiveness, limitations, and broader applicability of immersive virtual reality (VR) for tactical medicine training. The findings are interpreted in light of the original research questions and hypotheses, and situated within the context of existing literature.

6.2.1 Interaction Method: Validation of Hand Tracking

The study strongly confirmed the hypothesis that natural hand tracking is perceived as more intuitive and effective than controller-based input for medical tasks in VR. Participants repeatedly emphasized that interacting directly with virtual equipment using their hands felt closer to real-life procedures, enhancing both realism and ease of learning. This aligns with previous findings from Schild et al. [SLML18], who demonstrated that embodied interaction enhances spatial awareness and muscle memory in immersive training environments. Similarly, Sridhar et al. [SMZ+16] found that hand tracking interfaces supported faster acquisition of procedural skills and improved task completion times.

The readiness and accessibility of Meta Quest 3's built-in hand tracking also contributed significantly to this outcome. Unlike earlier XR systems that relied on external sensors or marker-based gloves, Meta Quest 3 enables natural interaction without additional hardware—lowering barriers for both developers and trainees. In comparison to systems used in projects like EPICSAVE or MED1stMR, which often require complex setups with manikins and external tracking, the standalone solution in this study illustrates how recent advances in consumer-grade VR can support effective training with minimal technical overhead.

However, several participants also noted limitations—particularly in precision and feedback. Certain interactions, such as rotating a tourniquet or performing stable side positioning, remained difficult due to current tracking constraints. This echoes findings by Lederman et al. [LSL20], who noted that fine motor actions still present challenges in VR unless haptic guidance or adaptive gestures are implemented. Future iterations should consider hybrid approaches, combining hand tracking with lightweight haptic feedback or guided gesture recognition to support high-fidelity medical simulations. Additionally, full-arm tracking—at least up to the elbow—could improve realism and reduce errors in actions that involve broader arm movement, such as applying pressure, rotating a tourniquet, or stabilizing a patient.

6.2.2 Scenario Realism: Contextual Information vs. Environmental Triggers

Contrary to the first hypothesis, the study revealed no substantial difference in immersion or emotional response between participants who were informed about the real-life inspiration for the simulation and those who were not. While the use of a real-world scenario added conceptual relevance, it did not appear to directly heighten psychological stress or presence.

This outcome resonates with arguments made in Slater and Sanchez-Vives [SSV16], who stress that immersion in VR is more a function of real-time environmental reactivity than narrative background. Participants in the study highlighted the importance of ambient sound, urgency, movement, and multi-sensory stimuli in shaping emotional involvement. For instance, multiple interviewees suggested that the environment was "too clean" or "predictable," and recommended adding noise, darkness, or unpredictable bystanders to more accurately simulate field conditions.

From a design perspective, this suggests that developers should prioritize situational variability and reactive cues over narrative complexity. The importance of dynamic environmental stressors has also been emphasized in trauma simulation studies, such as those by Davis et al. [DVPA20], who found that auditory stressors were more effective than visual realism in inducing measurable cognitive load in trainees. These insights can inform future development toward creating psychologically engaging simulations with higher affective fidelity.

6.2.3 Training Efficacy and Integration Potential

The results provide strong support for the role of VR as a supplemental training tool. Participants noted the simulation's value in familiarizing users with tactical workflows, decision-making under pressure, and injury-to-treatment associations. This reinforces the findings from projects like VIREM and SIMXVR [AAS+14, ELC+22], which showed that virtual simulations can accelerate procedural understanding and improve knowledge retention when paired with physical training.

However, consistent with previous literature, the simulation was not viewed as a replacement for hands-on drills or manikin-based training. As stated in works by Wiederhold [Wie18] and recent NAEMT whitepapers, VR is most effective when integrated into blended learning models. The participants' suggestions—such as combining VR with field days, classroom instruction, or team-based drills—reflect a pragmatic understanding of how immersive technologies can enhance, rather than supplant, traditional pedagogy.

Interestingly, none of the participants had previously encountered VR-based tactical medicine training, despite their experience with first aid or emergency response. This confirms the current gap in deployment, especially in the German-speaking regions, and highlights a potential for broader adoption. As pointed out by Feng et al. [FGA+18], the key to widespread integration lies not just in technological capability, but in accessibility, repeatability, and pedagogical alignment.

6.3 Limitations

While the project successfully delivered a functional and immersive VR training prototype, several limitations were encountered during development that may affect the generalizability or realism of the simulation:

- **Hardware Limitations for Fine Motor Interactions:** One of the most significant constraints was the limited fidelity of current hand tracking technologies. Specifically, natural hand tracking on the Meta Quest 3 does not reliably capture forearm orientation, which is critical for simulating procedures like applying a tourniquet. In real-world scenarios, the application involves rotational leverage of the entire forearm and elbow—movements that cannot be reproduced with the current input system. As a result, interactions like turning the windlass of the tourniquet had to be approximated or abstracted through animations and scripted logic.

- **Simplified Medical Procedures:** Due to technical and design constraints, certain medical interventions had to be simplified. For instance, detailed physiological responses (e.g., bleeding rate, airway obstruction behavior) were not fully simulated, and patient responses to treatment were scripted rather than dynamically driven.
- **Environmental Constraints During Testing:** During the user study, a few participants occasionally required clarification or assistance from the researcher. In such cases, the simulation volume had to be lowered temporarily to facilitate communication. While necessary, this adjustment slightly broke immersion and disrupted the continuity of the scenario. A more integrated solution—such as in-simulation voice communication or a built-in help system—could improve usability and preserve immersion during real-time guidance or troubleshooting.
- **Limited Participant Diversity:** While all participants had some form of first aid or tactical medicine experience, the sample size was relatively small (N=10) and demographically skewed toward male participants. This may limit the generalizability of findings related to user perception and preferences.
- **Restricted Communication Interface:** In the current version of the simulation, users could only communicate with virtual characters through predefined instructions and dialogue options. While sufficient for structured training purposes, this limitation reduced the realism and flexibility of interaction, especially in scenarios where natural speech would be expected. Voice input could offer a more fluid and intuitive experience but was not implemented due to technical constraints.
- **Single Scenario Focus:** The simulation focused on a single, knife-related mass casualty scenario. While this offered a high degree of narrative coherence, it limited the opportunity to test broader adaptability across other emergency types (e.g., chemical incidents, active shooter scenarios).
- **Lack of Multiplayer Functionality:** The simulation was designed as a single-player experience, which does not reflect the reality of tactical medicine, where teamwork and role distribution are essential. While a multiplayer mode was initially considered, it was ultimately excluded due to technical complexity and the challenges of testing and synchronizing multi-user sessions. Future versions could explore collaborative VR settings that support team coordination and communication.
- **Limited Emotional and Physiological Simulation:** The virtual patients did not display detailed emotional reactions such as fear, shock, or pain expressions. Similarly, physiological markers (e.g., pulse, respiration) were not simulated in

a way that required close monitoring. This reduces the complexity of patient assessment and may limit the realism of the training.

These limitations do not diminish the utility of the simulation, but they highlight the importance of future iterations that may incorporate more advanced tracking hardware, haptic devices, or expanded scenario content to further improve realism and effectiveness.

CHAPTER 7

Conclusion and Future Work

This chapter summarizes the key findings of the thesis and reflects on the implications of the research questions. It also outlines potential future work and possible improvements to the VR training system developed. The full project source code, including Unity scenes, scripts, and selected assets, is available on GitHub [Tre25]. This repository is intended to support further academic exploration and practical applications in XR-based medical training.

7.1 Conclusion

This thesis presented the design, development, and evaluation of an immersive virtual reality (VR) training simulation for tactical medicine, targeting first responders and trainees. TacMedVR project aimed to recreate high-stress emergency scenarios with a focus on usability, realism, and educational value. Built using Unity and deployed on the Meta Quest 3 platform, the system integrates hand tracking, patient interaction, dynamic scenario logic, and communication modules to simulate real-world triage and treatment workflows.

The study investigated three primary research questions: (1) whether scenario realism—particularly when based on real-world events—affects immersion and stress perception, (2) how different interaction methods (hand tracking vs. joystick control) influence usability and effectiveness, and (3) how participants perceive the potential of VR as a substitute or complement to traditional physical training.

Qualitative feedback gathered from ten participants—most with prior tactical medical experience—showed strong support for the educational potential of the simulation. Participants praised the intuitive nature of hand tracking, the immersive audio-visual environment, and the ability to rehearse critical interventions in a safe, repeatable format.

However, the findings also revealed technical limitations such as gesture recognition inconsistencies and restricted communication methods.

One of the key takeaways is that the realism of the environment alone does not necessarily elevate immersion unless it is supported by dynamic interactions, meaningful variability, and responsive system behavior. While hand tracking was generally favored over joysticks for realism, some users noted the need for fallback options when precision or feedback was lacking. Finally, participants overwhelmingly viewed VR as a promising complement—but not a replacement—for physical simulation, particularly for skill rehearsal and scenario familiarization.

7.2 Future work

Several promising directions exist for refining and expanding the current TacMedVR prototype. Building on the encouraging results of the user study and feedback from domain experts, future iterations could focus on increasing realism, interactivity, and scalability:

One of the most significant opportunities lies in the implementation of **natural language interfaces**. Currently, interaction with bystanders and patients is limited to predefined contextual options. Integrating speech recognition and AI-driven dialogue systems could allow trainees to issue verbal commands, comfort patients, or gather information through conversation—more closely mimicking real-world communication. Similar approaches have been explored in recent XR research, such as the AI-supported training system proposed by Pretolesi et al. [PZSF+23], which personalizes emergency response learning using conversational agents and dynamic scenario adjustment.

Another avenue is the inclusion of **expanded trauma scenarios**. The current simulation focuses solely on knife-related injuries; however, real-world emergencies often involve a range of trauma types. Future development could incorporate burn victims, blunt force trauma, airway compromise, or blast injuries—providing a more comprehensive training platform that addresses both civilian and combat medical needs.

Multiplayer functionality also remains an important area for future work. Tactical medicine is inherently team-based, and introducing support for co-located or remote multi-user sessions would allow for realistic team coordination, role distribution, and communication training. Instructor-driven scenarios, where trainers can trigger new events or provide in-simulation guidance, would further increase pedagogical flexibility and allow for adaptive feedback during live sessions.

From a technical standpoint, improving **body interaction fidelity** is essential. As participants noted, interactions like tourniquet application or placing a patient into a recovery position require more than just finger tracking. Extending the current hand-tracking system to include elbow position, forearm rotation, or full-body inverse kinematics (IK) would enable richer procedural training. Future iterations may also benefit from integrating lightweight haptic devices to simulate touch, resistance, or pressure feedback—especially for fine motor tasks.

Finally, the simulation could benefit from **automated performance analytics**. Real-time evaluation of user actions, timing, and decision-making can be logged and analyzed to offer immediate feedback or generate personalized debriefing reports. These features would align well with competency-based medical training models and support longitudinal skill development.

Overall, this work contributes to the growing body of evidence supporting immersive XR as a viable and impactful tool for emergency medical education. When combined with domain-specific expertise, user-centered design principles, and emerging technologies such as AI and haptics, VR training systems like TacMedVR can play a vital role in preparing responders for the emotional and procedural challenges of real-world emergencies.

Overview of Generative AI Tools Used

This thesis utilized ChatGPT (OpenAI, GPT-4) to support the writing process. It was employed for restructuring content, refining academic language, and clarifying methodological frameworks. All substantive decisions, final content, and research interpretations were made by the author.

No content was generated using image-based generative AI tools such as DALL · E or Midjourney.

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