Prototyping and Evaluation of a Lightweight Simulator Concept Combining Physical and Digital Assets

Master's thesis in Computer science and engineering

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Cover: A virtual soldier with a gunshot wound getting treatment from a trainee using VR.

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Abstract

Serious injuries often occur in high-risk environments such as warfare, urban combat, and traffic accidents. The medical proficiency of soldiers and first responders in these situations is paramount. However, traditional training practices frequently fall short, failing to replicate the stress of these environments accurately and involving substantial logistical efforts and personnel, leading to high costs and poor scalability. Meanwhile, virtual reality (VR) has shown promise as a cost-effective and immersive training tool in related areas.

This thesis investigates the feasibility of a mixed reality (MR) training solution for combat casualty care, aiming to blend the immersive environments of VR with the tactile interaction of physical props. Through the development of a prototype, using Design Research Methodology, various challenges were identified, evaluated, and addressed.

The MR training simulator demonstrated potential as a cost-effective alternative that offers a more realistic and immersive training experience. A software-based approach allows for standardization thanks to the replicability of training scenarios and the collection of user performance data. However, the seamless integration of physical assets proved challenging, primarily due to tracking inaccuracies and a lack of real-world visual feedback.

Medical MR training research is still in its early stages, particularly regarding accurate tactile interaction with digital and physical objects. However, as demand for MR training solutions continues to grow, it's expected that advancements in this field will follow.

Keywords: Virtual reality, extended reality, mixed reality, tactical training, simulation, combat, medical, treatment, tccc, unreal engine.

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Nicke Carlsson & Carl Månsson, Gothenburg, June 2023

Contents

List of Acronyms

AR augmented reality
ATLS advanced trauma life support
AVRT Adaptive Virtual Reality Training
AVRT Military Adaptive Virtual Reality Training Military
CCP casualty collection point
CUF care under fire
DOD R&D Department of Defense's Research and Development
DRM Design Research Methodology
FPS frames per second
HMD head-mounted display
MARCH massive hemmorhage, airway, respirations, circulation and head injury/hypothermia
MR mixed reality
MTF medical treatment facility
NPC non-player character
PS potentially survivable
TCCC Tactical Combat Casualty Care
TFC tactical field care
UE5 Unreal Engine 5
VALOR Virtual Advancement of Learning and Operational Readiness
VH virtual human
VR virtual reality
XR extended reality

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Introduction

1.1 Background

Warfare always comes with numerous fatalities. It's an unfortunate fact that some of these result from wounds that, under different circumstances, could have been survivable with the appropriate care. According to an article analyzing U.S. Military presence in the Iraq and Afghanistan wars 2001–2011, 24.3% of deaths were deemed potentially survivable, and among these, 90.9% were associated with hemorrhage, or bloodloss [1]. Another article discussing the casualties of the Vietnam war found that 7.4% of all deaths were caused by hemorrhage [2], and could have been prevented if the bloodlosses were stopped in time.

Soldiers function not only as combatants but also as first responders. In these critical moments, the life of an injured soldier may rely on the immediate actions of their fellow servicemen. If every soldier is equipped with essential field medicine knowledge, many more lives can be saved.

However, the provision of first aid and medical care under the extreme conditions of a battlefield is far from straightforward. It requires not only accurate memorization of procedures, but also the ability to apply them correctly in high-stress circumstances. Traditional methods of medical training can impart knowledge and basic practical skills, but simulating the high-stress, high-stakes environment of a battlefield is challenging. Additionally, these methods often require significant organization and personnel, making repeated arrangements expensive and time consuming.

Improving first aid education is not only relevant from a military point of view, but will also lead to overall higher medical knowledge in society, which is applicable in other emergency situations. Within other occupational groups with similar challenges, such as police, criminal investigators and security guards, a low-cost solution would make it more affordable for anyone to pursue. A clear connection can be drawn between improving medical knowledge and bettering our society, by looking at UN's 17 Sustainable Development Goals [3]. The goals were created as a means to more strategically work towards the 2030 Agenda for Sustainable Development, to reach peace and prosperity for people and the planet. Goal number 3 aims to "Ensure healthy lives and promote well-being for all at all ages". By increasing the number of people capable of providing proper first aid treatment, the likelihood of someone nearby being able to help in an emergency increases. Sub-goal 3.1 explicitly targets deaths and injuries from road traffic accidents - which is the type of emergency where this knowledge could be life-changing. Sub-goal 16.1 targets violence and related death rates. If a trained civilian or police were to arrive at a scene and find someone hurt, having training in first-aid medicine could make all the difference in keeping them alive until an ambulance arrives.

In recent years, virtual reality (VR) technology has seen tremendous growth and adoption across various industries. One such area where VR has shown significant potential is in the realm of medical education and training [4]. The incentive for increasing the effectiveness of medical training for soldiers is evident and the challenge lies in developing and implementing the methods to achieve it. As this thesis will discuss, VR holds considerable potential as a tool for immersive and realistic training that could ultimately help to reduce fatalities in combat.

1.2 Related Work

In recent years, various extended reality (XR) solutions have emerged with the aim of enhancing the training of military personnel. This section discusses four such initiatives that share similarities with this project, though with some distinct differences and limitations.

In 2022, the Army Medical University in China published an article identifying certain disadvantages of current training methods for first aid, and created a scenario-based, mixed reality (MR) platform to study and determine if it could prove effective in improving nontechnical skills within first-aid [5]. The platform used realistic MR environments and modeled their scenarios from real-world training scenarios that combined critical medical decision-making with teamwork and the threat of enemy forces. The focus on nontechnical skills meant none of the decisions were exercised, but instead presented as dialog boxes. The trainees would then attempt to select the correct action from a number of options. The results implied that this form of training was helpful in improving both team cooperation and first aid decision-making. However, the lack of technicality meant there was no improvement in technical ability. It would have been interesting to see a similar solution with this as its focus, considering this was a MR implementation, which unlike strictly VR solutions allows for the integration of physical objects.

AVRT Military, developed by Adaptive Virtual Reality Training (AVRT), provides an immersive VR environment for soldiers to train in [6]. It captures detailed metrics of the trainee's actions, including shot placements, reaction times, distances, and biometric data. Additionally, the system provides post-session reviews, enabling the trainee to replay scenarios from their own perspective. While AVRT Military's focus is on combat training, which differs from the casualty care angle of this project, its concept for capturing intricate data from the simulation could be utilized to gauge performance and track progress over time.

VALOR, created by SimX and funded by the Department of Defense's Research and

Development (DOD R&D), simulates military healthcare training scenarios [7]. The program, whose name stands for Virtual Advancement of Learning and Operational Readiness, presents high-fidelity, repeatable scenarios that operate on cost-effective hardware. However, the approach used for VALOR lacks one key aspect that this project aims to address - physical interaction with care equipment. VALOR's scenarios are entirely virtual, placing more emphasis on recognizing the subsequent step in a process rather than on optimally performing these steps.

After formalizing TCCC into its pre-hospital care training in 2007 [8], the French Military Medical Service identified the massive expenses of conducting a day of initial training and an ongoing series of half-day courses annually for over 80 000 soldiers. To address this, in 2014 a serious game was developed called 3DSC1 which would take care of the initial stages of the training program. The benefits of this solution were not only economical, but also allowed soldiers to train in a wide variety of different scenarios, any number of times, in any place at any time. However, like other VR solutions it suffered from the same weakness of not being suitable for hands-on training as there was no integration of physical props [9].

This project takes inspiration from these existing solutions but aims to bridge the gap between virtual simulation and physical interaction, thereby offering a more comprehensive training experience.

1.3 Aim

The aim of this report is to comprehensively examine the current state of combat medical training, with the intention to identify potential areas of improvement that could enhance survival rates on the battlefield.

One important goal is to evaluate VR as a potential tool for enhancing training experiences. The incorporation of VR into training regimens may offer more realistic and immersive scenarios, potentially leading to better prepared soldiers and more cost-effective training methods.

Furthermore, this report explores the utility of a mixed reality (MR) solution, which combines the immersive environments of VR with physical props to assess the value of accurate interaction between trainee and medical tools. The ambition is that the insights derived from this MR approach contribute to the future of combat medical training and add to the ongoing discourse in related fields.

1.4 Delimitations

To ensure that the most critical cases are handled first, based on the TCCC, first responders are instructed to follow MARCH, meaning they should treat casualties in the following order: massive hemmorhage, airway, respirations, circulation and head injury/hypothermia [10]. This project will focus specifically on massive hemorrhages.

The decision to focus on massive hemorrhages is not only because it's the most critical of the five, but rather the difference in survival rates which could be achieved through proper hemorrhage control. According to previous studies, approximately 50% of deaths in combat are caused by exsanguination, and 20% of these could potentially be preventable with the timely and correct application of pressure to the wound [1]. Therefore, developing effective training measures in this specific area has the biggest potential for saving lives.

This narrower focus should not be seen as a limitation but rather as a strategic approach to optimize the use of available resources, with a view to expand upon this foundational work in the future.

2

Methodology

This chapter outlines the research methodology employed for this thesis. It discusses research of the problems at hand, design of a prototypical solution, the techniques for analysis, evaluation and validation. The chosen methods were designed to provide robust, replicable results that adequately address the research questions.

2.1 Goal Description

The goal of this thesis is to develop and evaluate the effectiveness of an MR combat casualty care simulator that combines the advantages of virtual reality with the utilization of physical props, to provide an immersive, cost-effective, and scalable training solution for the military and and first responder sectors. By investigating the challenges and difficulties associated with combat training, this thesis aims to enhance the efficiency and effectiveness of combat casualty care education, ultimately contributing to better patient outcomes on the battlefield. To achieve this goal, three research questions were produced to guide the thesis.

2.1.1 What are the barriers towards achieving a quality, effective and good-practice VR training in tactical care?

One of the objectives of this research is to investigate the difficulties and challenges that may be encountered when developing and implementing a high-quality, effective, and good-practice VR-based training solution for tactical care. Identifying these barriers is essential for ensuring its successful integration into military and first responders medical education.

One potential barrier to achieving quality VR training in tactical care involves technical limitations and challenges associated with virtual reality technology. These may include issues with hardware performance, software compatibility, and realistic simulation of complex environments and scenarios. By addressing this research question, the study aims to identify specific technical challenges and explore potential solutions for overcoming them in the development and implementation of the VR simulator.

2.1.2 How can digital and physical assets be combined in MR training for tactical care, and how can we measure success?

This thesis also examines the integration of digital and physical assets in MR training for tactical care and explores the methods for measuring success. Combining digital and physical elements effectively can enhance the immersive and realistic nature of the training experience, while measuring success is crucial to assessing the impact of the XR simulator on learning outcomes.

To address the question of how digital and physical assets can be combined in MR training, this study will investigate the concept of hybrid training environments. These environments utilize both virtual reality technology and physical props or equipment to create a more immersive and engaging training experience. This research question seeks to explore the design principles, implementation strategies, and potential challenges related to the effective integration of digital and physical assets in MR training for tactical care.

Furthermore, this research question emphasizes the importance of continuous improvement and iterative design in the development and implementation of the MR combat casualty care simulator. By understanding how to effectively combine digital and physical assets in MR training and measuring success, the research can inform the ongoing refinement and optimization of the simulator, ensuring its relevance and effectiveness in the evolving landscape of tactical care education.

2.1.3 What can be learned from applying MR training to tactical care?

The third research question in this study seeks to understand the broader implications and lessons that can be derived from applying virtual reality training to tactical care. As this Master Thesis focuses on the development and evaluation of a MR combat casualty care simulator, it is crucial to explore the potential impact and transferability of this technology to other areas of military training and beyond.

By investigating the application of MR training to tactical care, this research aims to identify best practices, effective techniques, and potential areas for improvement that could be valuable for enhancing training in related disciplines. These insights can help inform future developments in virtual reality training solutions, not only for combat casualty care but also for other aspects of military education, such as tactical maneuvering, communication, and decision-making under stress.

Moreover, understanding the lessons learned from applying MR training to tactical care can provide valuable insights for other fields outside of the military context. Many industries and sectors, such as healthcare, emergency response, and law enforcement, require professionals to perform under high-stress situations, where effective training and preparedness are crucial. By analyzing the application of MR training in the context of tactical care, this research can contribute to the broader knowledge base on immersive training technologies and their potential interdisciplinary applications.

2.2 Design Research Methodology

The research conducted in this project largely draws on the principles outlined in the book "Design Research Methodology" by Blessing and Chakrabareti (2009) [11]. This comprehensive framework, abbriviated DRM, suggests four main stages of research. These are *Research Clarification*, *Descriptive Study I*, *Prescriptive Study*, and *Descriptive Study II* stages. The methodology suggests a cyclic nature, where the results and insights from the final stage feed back into the initial stages, refining and updating the research objectives and methods.

2.2.1 Description of DRM Stages

Research Clarification: This is the initial stage where the research problem is identified, the aim and objectives of the study are defined, and the research questions are formulated. It's a stage that requires understanding of the problem at hand, the relevant theories and studies related to it, and the gaps in the current knowledge that the research aims to fill. This stage ends with a clear research plan.

Descriptive Study I: In this stage, existing solutions or practices are studied in-depth. It can involve various methods such as case studies, surveys, or experiments, and should result in a detailed understanding of the current state of the art. The data gathered at this stage becomes the basis for the development of new solutions or improvements in the next stage.

Prescriptive Study: This stage involves the generation, development, and evaluation of new solutions based on the understanding acquired from the previous stages. The newly proposed solutions are then tested and refined through an iterative process. The output of this stage is a design that addresses the research problem defined in the first stage and is validated by the data gathered in the second stage.

Descriptive Study II: The final stage involves assessing the impact of the newly implemented solution. The solution is evaluated against the research objectives defined in the first stage. This stage is crucial for understanding the effectiveness of the proposed solution and learning for future design improvements in the next cycle of stages.

2.2.2 Adaptation for this Thesis

This iterative approach to research and design served an important role in guiding this project towards its aim of exploring the potential of VR in enhancing casualty care training. To ensure a clear pathway was entertained through the project, the workload was divided into tasks with deadlines, visualized using a Gantt Chart. The objective remained to follow this plan as closely as possible to ensure deadlines were met, but as the project developed and morphed, it would sometimes be counterproductive to keep a too strict schedule, and adjustments were made.

The research of this thesis began with a thorough literature study in accordance with the first stage of DRM to get a solid understanding of the overarching problem: avoidable deaths in combat situations. The literature study continued to the second stage, as the team reviewed current solutions to improving the effectiveness of tactical medical training, what they did good and where they fell short in comparison to traditional teaching methods. When a clear picture of the problem and current situation had been acquired, design and development of a prototype ensued.

The iterative process of DRM was then followed throughout the project, ensuring continuous evaluation of the prototype and recognising areas in need of improvement. To facilitate this cyclical feedback system, the development process was structured around an Agile project management approach [12]. The development period was divided into ten sprints of two weeks each, with evaluation meetings every other sprint, as further detailed in the next section.

2.3 Evaluation and Validation of the Simulator

The functionality, usability, and effectiveness of the simulator were assessed through an evaluation process that comprised functional testing, usability testing, and professional validation. Every four weeks, the project group met with a team of people trained in combat medicine to demonstrate progress of the simulator and receive feedback for future development. This iterative approach of the agile development methodology ensured continuous progress and improvement throughout the project, and served as a valuable complement to theoretical literature studies in building a knowledge-base for the project group. The insights gained from these consultations are further detailed in Section 4.4.

2.3.1 Evaluation Process

Functionality and usability testing were primary components of the continuous evaluation process. Functional testing ensured the technical soundness of the simulator, focusing on the tracking system's accuracy, frame rate, and the integrity of the training scenario. Usability testing, on the other hand, assessed the intuitive nature of the simulator, paying close attention to the user interaction and response to the virtual environment.

The developmental phase of this project was concluded with three sessions of demonstrative testing with external people competent in various relevant fields. The goal of these sessions were to collect feedback about the final prototype and thereby build an understanding of how well the prototype serves in improving tactical combat care training, ultimately contributing to clarity for answering the research questions. Feedback from these demonstrations are discussed in Section 5.4.

2.3.2 Contribution to Validation

The fore-mentioned evaluation aspects significantly contributed to the validation of the simulator. Validation in this context pertains to the simulator's capability to closely mimic real-world medical scenarios and serve effectively as a training tool.

The accuracy of handholds assures that the simulator provides a realistic training environment, thereby boosting its credibility as a training tool. Such accuracy ensures the transferability of the skills learned in the simulator to real-world scenarios.

The capture and analysis of simulation data establish the simulator's efficacy as a training tool. It presents an objective means to measure the improvement in trainee skills and decision-making capabilities.

The agile approach used during the project development allowed for continuous evaluation and reconsideration after every sprint, and more thoroughly so after every other sprint – where meetings with experts occurred. Therefore, it was possible to integrate improvements iteratively and enhance the overall quality of the simulator.

3

Theory

This chapter covers key concepts and principles that underpin the field of tactical casualty care as well as virtual reality. It delves into essential topics that form a foundation of effective casualty care and training methodologies as well as tools utilized in the field of VR. These include warfare fatalities, the casualty care process, immersive training and the utilization of virtual humans. Each section offers valuable insight into different aspects of casualty care and VR, and sheds a light on prevailing challenges, strategies and advancements within the fields. By exploring these areas, the chapter sets the stage for the subsequent empirical investigations and practical applications discussed in later chapters.

3.1 Overview of Warfare Fatalities

As briefly mentioned in Section 1.1, studies of previous wars indicate that a considerable number of combat fatalities are caused by injuries that could have been prevented given better treatment. In *Death on the battlefield (2001–2011): Implications for the future of combat casualty care* [1], B. J. Eastridge et. al. analyze the casualties of U.S. soldiers in Iraq and Afghanistan. During a ten year period between 2001 and 2011, a total of 4,596 U.S. soldiers died in the battlefield. Among these, 580 died from wounds after being transferred to a medical treatment facility (MTF). The other 4,016 died before getting access to the professional medical treatments available at the MTF.

The study goes on to describe that 24.3% of all casualties were deemed potentially survivable (PS), meaning that 976 soldiers could potentially have survived if they had received proper treatment in time. The vast majority (90.9%) of PS causalities were results of hemorrhage. A graphic representation of these numbers can be found in Figure 3.1. A similar study of the Vietnam war examined a sample of 2,600 U.S. military deaths. Among these, 193 (7.4%) died from PS hemorrhage [2]. Applying the same ratio to cover all 46,233 U.S. casualties during the Vietnam war, it can be assumed that a total of 3,421 deaths from hemorrhage could have been prevented with proper and immediate care [13].

These statistics underscore the urgent need for effective hemorrhage control in combat scenarios. It indicates that significant improvements in battlefield fatality rates can potentially be achieved through better initial medical response. Thus, the importance of adequate training in combat care, particularly focused on hemorrhage

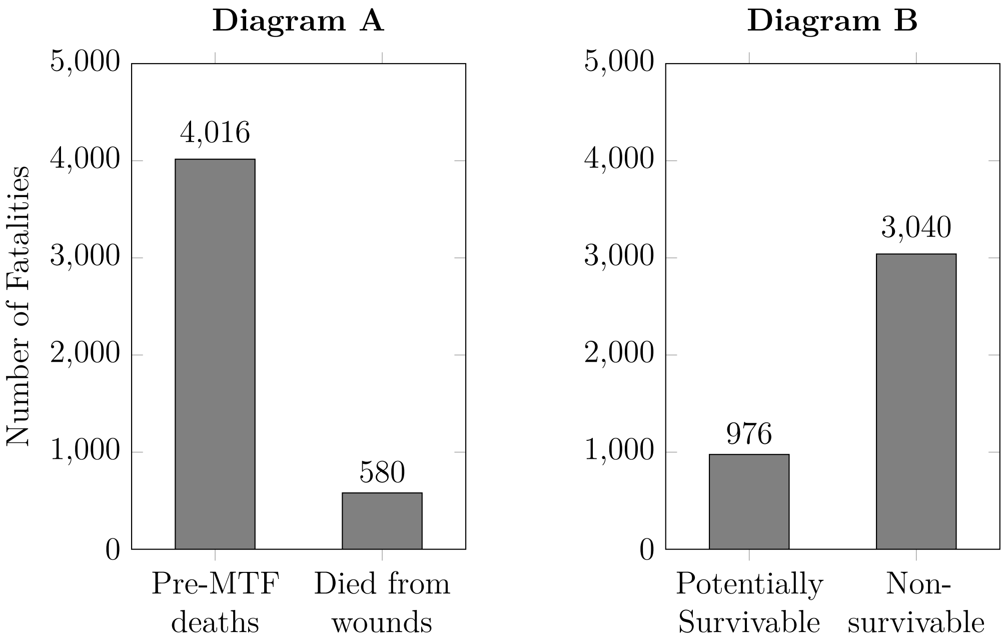

Figure 3.1: Diagram A: Most of the soldiers die before getting access to professional treatment at MTFs. Diagram B: A significant number of deaths were deemed potentially survivable [1].

management, becomes evident. Considering the high percentage of preventable fatalities due to hemorrhage, it is clear that optimizing methods of providing this training should be a priority.

3.2 Casualty Care Process

This section will cover what action to take given a scenario involving someone in need of medical care as well as the potential symptoms to look out for when someone suffers from massive blood loss to be able to identify how severe the injury is and how much longer they on average have to live if left unattended.

3.2.1 Phases of Care

During a military mission, there are more things to consider than treating an existing wound. To understand the appropriate order of operations, the TCCC handbook [10] discusses the different phases of combat and the correct application of tactics and medicine during them.

Phase one pertain to situations where you are in the middle of a tactical engagement, also referred to as care under fire (CUF). In these situations you should prioritize gaining fire superiority and securing a safe position outside the line of fire. Casualty care should be limited to a hasty application of a tourniquet as it's the most efficient way to save someone injured from dying, making it the primary medical goal during CUF.

	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**
Blood loss, ml	<750	750-1500	1500-2000	>2000
Volume, %	<15	15-30	30-40	>40
Pulse	<100	100-120	120-140	>140
Blood pressure	Normal	Normal	Lowered	Lowered
Pulse pressure	Normal/ Elevated	Lowered	Lowered	Lowered
Respiratory rate	14-20	20-30	30-40	>35
Mental status	Slight anxiety	Mild anxiety	Anxious/ confused	Lethargic

Table 3.1: ATLS-classification of hypovolemic shock [18]

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Phase two is engaged once effective enemy fire stops, this is usually when tactical field care (TFC) starts. A casualty collection point (CCP) is set up to create an area dedicated to casualty treatment and medical personnel are gathered there to treat the wounded. The treatment plan follows the TCCCs MARCH order of operation for severity of casualty care: massive hemmorhage, airway, respirations, circulation and head
injury/hypothermia.

Phase three is the final phase and refers to evacuation of casualties. For this endeavour, ambulance exchange points are established to transport them to safety. Treatment of casualties are also re-evaluated to ensure correct treatment.

3.2.2 Casualty Behaviour

The effects of a massive hemorrhage are most discernible from the symptoms caused by hypovolemic shock, which is a byproduct of the lack of oxygen being able to reach the wounded's brain as they lose significant volumes of blood [14]. The advanced trauma life support (ATLS) manual classifies hypovolemic shock into four grades -each describing the symptoms of a more critical state as can be seen in Table 3.1.

Every minute, the heart pumps an average of 5-6 liters of blood throughout the human body. This number increases to over 35 liters when measuring elite level athletes during exercise [15]. If an artery gets damaged, arterial bleeding will start, which is rapid, life threatening and difficult to control [16]. Although the decrease in pressure over time means the blood flow will start to gradually slow down, someone suffering from this type of injury will still on average bleed out within 3-5 minutes - if no proper medical care is applied [17].

3.3 Immersive Training

This section delves into the theory behind immersive training. It aims to address what importance immersion has in training environments by reviewing if training efficiency is correlated with realism in training scenarios. This is done partly by comparing traditional teaching methods and emerging immersive technologies, and explores their current application in tangent fields such as medical education. Additionally, this section should provide clarity in economics of different training methods, reviewing cost differences in traditional and immersive solutions.

3.3.1 Traditional Teaching Methods

Traditional methods of training, particularly in medical and military education, have often relied on didactic lectures, textbook learning, and 'see one, do one, teach one' practical experiences [19]. While these methods have their merits, they also have significant limitations. The passive nature of lectures and textbook learning can make it difficult for students to retain information and apply it in practical situations [20]. Furthermore, the 'see one, do one, teach one' model can present risks in high-stakes environments such as battlefield trauma care, as it may expose patients to novice practitioners [21].

To produce realistic training scenarios, traditional methods often require considerable investment in props. High fidelity medical mannequins, for instance, are widely used for practical training in medical education. However, these mannequins can cost several hundred thousand dollars each [22]. Moreover, to cover a variety of potential medical scenarios, different types of mannequins (adult, child, trauma, etc.) may be needed, leading to significant accumulative costs.

3.3.2 Immersive Technologies

VR is a technology that places users within a computer-generated 3D environment where they can interact with objects as if they were in the real world [23]. This immersive experience is enabled by hardware such as a head-mounted display (HMD) and controllers, which track the user's head and hand movements, respectively, allowing for real-time manipulation of objects within the virtual environment [24] [25]. One of the cornerstones of VR is the notion of presence - the feeling of being physically inside the virtual environment, which serves to augment the user's sense of immersion and interaction [26].

MR is a hybrid technology that merges real and virtual environments to produce new environments and visualizations where physical and digital objects co-exist and interact in real-time [27]. In MR, users are not completely cut off from the real world as in VR. Instead, they see all or some of the real world around them with virtual objects and environments integrated in their field of view. This is typically achieved through the use of a passthrough HMD, that is, a HMD with front facing cameras capable of capturing the real surrounds to be projected on the screens.

XR is used as an umbrella-term covering both VR and MR, as well as similar technologies like augmented reality (AR).

3.3.3 Extended Reality in Medical Education

In the field of education and training, XR technology shows substantial promise due to its immersive and interactive capabilities. The nature of VR allows learners to practice and hone their skills in a controlled, safe environment. This safety permits them to make mistakes and learn from them, without the risk of real-world repercussions [28].

Simulation-based medical education, a domain that includes VR, offers notable benefits over traditional teaching methods. Studies have shown that it can lead to improved learning outcomes [29]. An exemplary application of VR in this context is its use in surgical skill training. The incorporation of VR in surgical education resulted in enhanced skill retention and transferability to real-life surgical procedures [21].

XR in general, and VR in particular, has found use in civil medical care. The low-cost, portable solution in comparison to traditional training, made for a attractive selling point and willingness of adaptation [25]. In a review of virtual reality training in the field of surgery, students using VR in their training were found to be significantly faster in their surgical procedures, while also making fewer mistakes, as compared to students who did not use VR in their training [30]. In contrast, another paper examining the medical training of 82 nursing students found that there was no significant difference in skill transfer between a VR and traditional training solution. However, the VR solution was still shown to be the far cheapest option, thus coming out on top in regard to cost-efficiency [31].

3.3.4 Training Scars

The term "training scars" is used to describe the undesirable consequences that manifest as a result of inadvertently reinforcing errors in a training environment, to the extent that they become deeply ingrained habits in trainees. In a military, law enforcement, or emergency medical service (EMS) scenario, when faced with a crisis, developed training scars could be fatal to either provider or patient. Craig Hall, Lead Medical instructor at the U.S. Airforce, in an article on training scars [32] lists a number of key points to consider when developing training programs in order to avoid them.

1. Train as you fight: This is a concept more applicable in military scenarios than EMS. It emphasises the importance of providing realistic training that accurately reflects real-world scenarios. Instead of starting a scenario with a simple "Scene safe, BSI" call (a common call signal at the beginning of paramedic student scenarios), and immediately proceeding to focus on treating someone wounded, more realistic elements should be incorporated. This includes things such as donning proper equipment, scanning for potential hazards, and maintaining situational awareness throughout the entire scenario.

2. Provide realistic patients: By making the training scenarios more realistic, the learning experience is enhanced. An important way to achieve this is by moving away from instructor-guided scenarios and instead incorporate medically trained people capable of accurately portraying the victim - including its behaviors and responses to interventions.

3. Provide realistic scenarios: It's particularly common in EMS to restrict training to classroom environments, which makes students less capable at assessing the situation and identifying hazards when they are put in a real emergency situation. The more preferable method is to provide a realistic setting to train the students in these scenarios. They could for example be placed at a staged scene of a vehicle accident and be forced to play out the scenario from start to finish.

3. Provide realistic outcomes: It is a fact that not every attempt to solve a situation ends in success. Sometimes the outcome is unavoidable despite someones best efforts. This is also the case for EMS. With this in mind, it can be beneficial to incorporate not only the possibility of, but also the inevitable outcome of, not being able to successfully rescue someone. Learning to accept that not everyone can be saved early is an important lesson to lessen the negative effect it could have on someone's psyche once they experience it in real life.

3.3.5 Virtual Humans

Humans being represented in a virtual environment are called virtual humans (VHs) [33]. There are two types of virtual humans: avatars and agents, and they are identified based on their behaviour, or more specifically the source of that behaviour.

Avatars are VHs being controlled by a player. This is commonly achieved through technologies such as motion and face-tracking, to mimic the movement and expressions of a real person [34].

Agents are VHs being controlled my a computer algorithm. Agents are usually referred to as non-player characters (NPCs), and are in games often made to have very simplistic behavioural patterns. That's not to say they cannot be complex. In fact, there have been several studies incorporating more advanced forms of Agents in VR with promising results. By placing Agents as audience members in a virtual presentation setting, and customizing their behaviour to respond to the presenter in different ways, it's possible to treat social anxiety disorders [35]. And using Agents in pedagogical scenarios such as to assist healthcare professionals in conducting clinical tasks or to replace patients, has shown to be effective [36] [37] [38].

By combining the behaviours of avatars and agents, one can create a hybrid solution to play on certain strengths and cover certain weaknesses. Insufficiently accurate tracking equipment in an avatar-solution can be replaced with a computer algorithm to control that specific movement like you would for an agent. And more complex human behaviors can more easily be applied to an agent, such as the decision to glance in a direction at a certain time to draw a users focus there, by having that particular part of them be controlled like you would for an avatar [33].

3.4 Serious Games and Learning

Serious games can generally be described as games used for educational purposes. Many games incorporate new mechanics and require knowledge that players have to learn. In the context of games, these aspects are often perceived as enjoyable, while being disliked in traditional learning environments. In the paper *Why so serious? On the relation of serious games and learning* [39], Breuer and Bente discuss the relationship between games and learning, as well as best practices for combining them into a serious game that is both enjoyable and educational.

Not all games are equally suitable for educational purposes, and merely adding educational material to an enjoyable game is insufficient for creating an effective educational game. Several useful approaches should be considered when developing a serious game. Firstly, the particularly entertaining parts of the game can be offered as rewards for successful learning. Elements that users enjoy can be used to stimulate their interest and engage them in upcoming learning procedures. Lastly, the learning process itself should be designed to be entertaining, allowing users to express their mastery of knowledge or skills and derive enjoyment from it.

In another paper, *Classifying Serious Games* [40], existing serious games are categorized based on their target audience. The classification considers qualities such as primary educational content, primary learning principle, target age group, and platform. According to their findings, 63% of the 612 reviewed games were marketed towards academic education, specifically targeting elementary, middle, and high school children.

While this classification provides insights into the impact of serious games in the industry, Breuer and Bente [39] express concerns regarding the study's reliance on commercially available titles. This approach has the potential to marginalize future prospects of serious games by neglecting ongoing research applications. Pervasive gaming, augmented reality, and location-based gaming are increasingly being investigated as promising avenues for developing serious games, but they are underrepresented in current research.

As a proposed solution, Breuer and Bente suggest a more comprehensive categorization system, comprising nine categories to classify serious games: platform, subject matter, learning goals, learning principles, target audience, interaction mode(s), application area, controls/interfaces, and common gaming labels.

4

Results and Analysis

This chapter presents the key findings gathered throughout the course of this study. It assesses the current challenges faced in combat medical training, and explores the potential role of XR as a tool to mitigate some of these issues. Simultaneously, the analysis also brings forth the shortcomings of XR, and how to overcome them. These findings are a result of the methodology employed, as detailed in Chapter 2. By articulating these results, this chapter aims to present a nuanced view of the potential and limitations of XR in battlefield medical training.

4.1 Implications of Introducing VR in Combat Casualty Care

This first section aims to describe what VR can offer in terms of improvement in the field of combat casualty care training and its potential in similar fields. The section also highlights the limitations found with the use of VR and possible measures to mitigate such issues.

4.1.1 Challenges in Traditional Training Methods

While examining current training methods, a range of potential areas for enhancement were identified. This section will provide a detailed breakdown of four key areas that served as the foundation for design of a better solution.

1. Limited realism: Simulated casualties in field exercises often lack the fidelity and realism of actual injuries. This can lead to gaps in knowledge and skills when transitioning from training to real-world scenarios. There are also challenges in simulating the stressful nature of a real combat situation, leading to worse performance in medical care due to training scars from the calm environment of training scenarios.

2. Resource-intensive: Traditional training methods pose considerable demands in terms of resources, both in terms of physical assets and human capital. Firstly, there is a need for specialized equipment and tools that mirror the ones used in the field to foster a realistic training environment. These tools can be expensive to purchase, maintain, and replace.

Specialised training facilities can also contribute to expenses in traditional training. These locations need to be able to mimic realistic battlefield conditions as closely as possible for the training to be effective. Sourcing, maintaining, and booking such locations often pose logistical difficulties, requiring significant planning and coordination efforts.

3. Scalability: Traditional classroom lectures and hands-on practices have scalability issues, which restricts the number of participants and limits the frequency of training sessions. These constraints can potentially hinder the widespread maintainability of tactical care knowledge among trainees. Purpose-designed training facilities are also narrow in their target training scenarios and difficult to modify to suit different combat situations.

4. Inconsistency: Variations in instructor experience can lead to inconsistencies in training quality and content. This might affect the trainees, as their acquired skills could differ based on the teaching expertise and knowledge depth of their instructor. The uniformity of training, crucial for maintaining standard procedures in high-stress scenarios like battlefield medical care, could thereby be compromised.

4.1.2 The Potential of VR

The immersive and adaptable environments of extended reality applications showed promising capabilities that could play a role in addressing the problems of traditional training. This section attempts to describe how XR can be utilized to solve corresponding problems described in Section 4.1.1.

1. Immersive: XR can provide a realistic and immersive environment that closely replicates the stress and complexities of a battlefield scenario, allowing trainees to practice skills in a more authentic context.

2. Cost-effective: XR simulations can be more cost-effective compared to traditional training methods, reducing the need for expensive equipment, personnel, and facilities.

3. Scalability: Since VR hardware systems are independent from each other, the number of simultaneously served users is directly correlated to the number of available systems. That means training can be easily scaled up or down to meet training needs. Any software training simulator also allows for easier redesign of environments and objects to address many different combat scenarios without the need to reconstruct physical facilities to match the desired scenario.

4. Standardization: An XR simulator can provide consistent training experiences with standardized scenarios, minimizing variations in training quality and content. They can also be designed to allow for user performance tracking, providing real-time objective feedback for the trainee or instructor to analyze during or after each session. This data collection can also allow for broader data-driven improvements in training programs.

4.1.3 The Limitations of VR in Combat Casualty Care Education

Prior attempts to integrate VR and MR into training have also highlighted some problems that had to be considered in this report to propose a more effective alternative.

Realistic Handholds: VR faces a significant challenge in emulating the tactile feel and accurate handholds of physical tools. In real-world interactions, precise manipulation of tools often requires dexterity gained through experience. However, most VR systems today rely mainly on game-pad derived hand controllers with vibration as their sole feedback mechanism for user interaction, leading to a lack of realism and potential difficulty transferring VR-acquired skills to real-world scenarios.

This can be solved with the introduction of passthrough technology. By allowing part of the real world to visually bleed through into the simulated environment, the user is able to see important details such as their own hands and the medical tool. This introduces other questions, such as how transparent the passthrough should be. Optimally, it should be strong enough that the user can confidently make out the detailed position of their hands and medical tools. At the same time, if it's too strong, that defeats the purpose of a VR solution as the 3D graphics will be too transparent to convince the user they are in that environment - at which point the VR becomes entirely unnecessary. This is something that could be extensively researched further in the future to find the optimal balance.

Motion-sickness: VR applications have been known to induce motion-sickness and nausea to the user. There are many factors determining the severity of this effect, like how pleasant the virtual environment is, what sex the user belongs to, how much prior experience the user has with VR and their general susceptibility to nausea [41]. However, two primary contributing factors are low frame rates (below 90 frames per second (FPS)) and extended time spent in VR. In designing the proposed prototype, measures were taken to ensure high frame rates and brief training scenarios, thereby aiming to minimize potential motion-sickness.

4.2 Depicting Casualty Care in VR

This section presents the outcomes pertaining to the portrayal of wounded individuals and the simulation of blood flow in virtual reality environments. The investigation explores various approaches utilized to accomplish these objectives, evaluates their comparative efficacy, and identifies the specific characteristics that make certain solutions particularly suitable for this specific use case.

4.2.1 Casualty portrayal

In the context of virtual reality, the representation of a wounded soldier can be regarded as a virtual human, as elaborated upon in Section 3.3.5. Employing either an avatar, an agent, or a hybrid of both approaches entails specific advantages and disadvantages.

An avatar facilitates realistic interaction with the VH within the physical realm, enabling tasks such as applying a tourniquet with the appropriate sensory feedback. However, achieving this level of realism necessitates the utilization of advanced technology to emulate the behavioral characteristics of the individual controlling the avatar. Moreover, if the casualty is expected to replicate the symptoms of someone suffering from hypovolemic shock, the person behind the avatar would need to enact these symptoms while being mindful of the timing.

In contrast, an agent allows for the pre-programming of intricate behaviors that authentically mimic those of a wounded individual. This encompasses movements, facial expressions, and the manifestation of symptoms, ensuring consistent and realistic portrayal in the simulation. Nonetheless, the drawback of lacking physical interactability for the user is particularly significant, as the user should be able to acquire proficiency in the correct application of medical tools.

A hybrid approach combining elements from both avatar and agent paradigms could manifest in various forms. An effective hybrid model might entail the utilization of an avatar-like physical representation of the body to enable real-world interaction. Meanwhile, a computer algorithm would govern the expressions and symptoms of the VH, ensuring accuracy and consistency with the expected behaviors of a wounded individual at any given time. Nonetheless, such an approach would still necessitate the employment of body-tracking equipment, and the real-life individual controlling the VH would still need to engage in a certain level of acting to enhance the believability of the scenario. This hybrid method capitalizes on the strengths of avatars and agents while mitigating potential drawbacks, making it well-suited for this specific use case.

4.2.2 Blood Flow Dynamics and Hemorrhage Progression

To establish a realistic representation of blood flow rates for wounded individuals, the findings from Section 3.2.2 were utilized. Considering that the average time of death following a hemorrhage is generally reported as 3-5 minutes, and blood flow tends to increase after physical exertion, a benchmark of 2.5 minutes was adopted to simulate the timeframe for an individual to bleed out. By incorporating the symptoms of hypovolemic shock, as also outlined in Section 3.2.2, the plot was divided into distinct sections, as depicted in Figure 4.1.

The initial section of the plot corresponds to the immediate aftermath of the hemorrhage, where the casualty has not yet experienced significant blood loss. During this stage, blood pressure and pulse pressure remain elevated, thereby maintaining

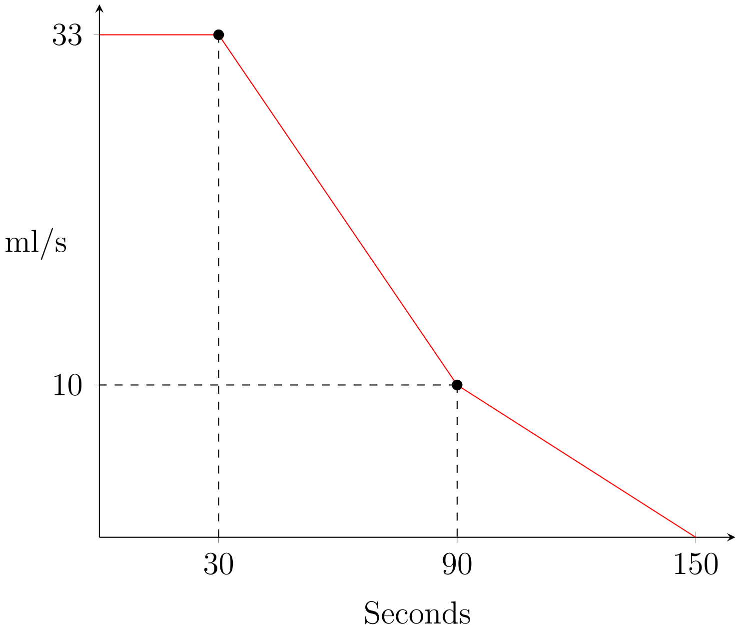

Figure 4.1: Blood loss over time for casualty with hemorrhage.

stable blood loss and a relatively high blood flow rate. Subsequently, as the casualty continues to lose blood and progresses to the next stage of hypovolemic shock, the decrease in blood volume becomes sufficient to gradually reduce blood flow over time. This trend persists until a certain point is reached, beyond which the decline in pressure becomes less pronounced, as indicated in the table where no identifiable difference in pressure is observed between the last two stages.

After approximately 150 seconds, the wounded individual reaches a critical point of exsanguination, resulting in the complete cessation of blood flow. It is important to acknowledge that due to the limited availability of definitive research on the precise dynamics of blood loss, and considering its significant variations across different cases, several assumptions were made during the analysis. Nonetheless, within the context of its intended application as a VR training simulator, the simulation adequately fulfills its purpose by instilling a sense of agency. Moreover, it demonstrates discernible temporal changes in blood flow, akin to the ATLS-classification-based table, thereby facilitating the classification of the casualty's condition severity.

4.3 Serious Game Classification

Using the categorization of serious games created by Breuer and Bente [39], introduced in section 3.4. A tactical casualty care simulator implementation based on the results of this chapter would be categorized as seen in Figure 4.1.

Label/Tag Category	**Labels**
1. Platform	Personal Computer
2. Subject Matter	War, Emergency Situation, Tactical Casualty Care
3. Learning Goals	Environmental Awareness, Decision Making, Medical Application Skills
4. Learning Principles	Observational Learning, Trial and Error, Conditioning
5. Target Audience	Military Recruits, Police Recruits, First Responders
6. Interaction Mode(s)	Single Player, Tutoring Agents
7. Application Area	Professional Training, Academic Education
8. Controls/Interfaces	Head Mounted Display (HMD), Body Trackers
9. Common Gaming Labels	Simulation, Strategy, Action, Role-play

Table 4.1: Classification of the lightweight simulator concept as a serious game.

4.4 Dialogue with Medically Trained Personnel

To complement the theoretical knowledge gathered from comprehensive literature studies, an ongoing dialogue was held with medically trained personnel to gather additional information and feedback on the progress of development. Two critical facets they emphasized throughout the development were the precision of handholds in the simulation and the collectibility of data for instructional purposes.

The accuracy of handholds was described to be of high importance for realistic medical training, as it forms the foundation for various medical procedures such as tourniquet application. As briefly discussed in Section 1.2, this key aspect was found to have been lacking in previous attempts to integrate VR in combat casualty care training.

Data collectibility was also of high importance. The ability to record user actions and decisions during the simulation offer insightful data to instructors for an objective assessment of the trainee's performance, decision-making process, and areas for improvement. Therefore, these aspects played an extra important role in guiding the development of the proposed solution.

5

Design and Implementation

This chapter offers an in-depth look into the development of the final software prototype. It explores the core considerations and decisions made during the project, providing a clear overview of both the design process and implementation details. Choices of hardware, the rationale behind design decisions, and specific implementation strategies are all discussed to present a comprehensive understanding of the developmental process.

5.1 Design Specifications

This section describes the initial design principles and restrictions that outlined the ambition for the prototype.

5.1.1 Hardware Requirements

The development of an MR simulator required careful consideration of hardware performance. Given the importance of sustaining a high and consistent frame-rate in VR applications, to both avoid motion sickness and preserve the immersive aspect of the virtual environment, it was essential that the simulator operated with minimal lag. At the same time, to allow for portability and widespread access, the simulator should be compatible with a standard, modern laptop, and not reliant on high-end, specialized hardware. Consequently, performance parameters were set to maintain approximately 90 FPS on a laptop equipped with a 1660 Ti graphics card, representative of a contemporary mid-range laptop.

5.1.2 Physical Interaction

The efficacy of the simulator hinges upon the authenticity of the trainee's physical interactions with medical equipment. The tactile sensation and direct manipulation of these tools are crucial aspects of real-world combat scenarios. To maintain the highest fidelity in these interactions, it was important to ensure that the virtual aspect of the simulator did not impede or modify the trainee's hands-on experience with the physical tools. This focus on physical interaction guided subsequent design and implementation choices.

5.2 Development

In this section, a detailed explanation of the developmental process is outlined. The goal is to give a deep understanding of the design choices made and the reasons they were deemed justified. It also provides in-depth descriptions of the different tools and assets used for development.

5.2.1 Choice of Game Engine

The choice of game engine is a critical aspect of the development process. It dictates the capabilities of the simulator, performance, and the potential for future expansion and modifications. For this research, Unreal Engine 5 (UE5) was chosen over Unity. Both are leading platforms in game development and have been used in various applications, including VR simulations. However, this choice was made this based on several key considerations.

Performance in VR simulations is a major factor in the immersive experience. This simulator is required to run at a consistent high frame-rate on portable consumer hardware to avoid motion sickness while maintaining portability. UE5 offers superior performance in high-fidelity VR simulations compared to Unity. This is partly due to UE5's advanced rendering capabilities, which allows it to handle complex, realistic graphics more efficiently.

Cache transfer efficiency was another important consideration. Our research indicated that Unity may encounter issues with cache transfer lags, which can affect the smoothness and responsiveness of the simulation. This issue was notably avoided by SAAB, who chose Unreal Engine for their applications.

Unity is known for offering an intuitive user interface and easy access to development tools which makes it a suitable starting ground for novice game developers and a fast, iterative development platform for more experienced developers. However, while UE5 has a steeper learning curve, its performance, features, and efficiency made it the more appropriate choice for this project. Its robustness and scalability also make it more suitable for potential future expansions.

5.2.2 Choice of VR System

Choosing the appropriate VR system was influenced by many factors, including cost, adaptability, compatibility, and user experience. With an abundance of choices on the market, four VR systems were considered more carefully: Varjo Aero, HTC Vive Pro 2, Meta Quest 2, and Valve Index.

The Varjo Aero is by far the most capable solution, but was disregarded due to its high cost. The other end, Meta Quest 2 offers a robust VR experience for a very good price, but it was found to be less adaptable and overly confined within the Meta ecosystem, posing challenges for the project's specific requirements.

The selection process then narrowed down to the HTC Vive Pro 2 and the Valve Index. Both compatible with the OpenVR API (formerly SteamVR). This also meant they allowed for integration with the HTC Vive Trackers. The Valve Index is well-known for its superior hand controller capabilities, including accurate finger tracking which can enhance interaction in VR environments. That said, the decision was made against it. The project design didn't incorporate hand controllers at all, prioritizing real-world interaction with physical props for more tactile authenticity. Hence, the HTC Vive Pro 2 was selected. Its high-resolution display facilitates a richly detailed and immersive VR experience. It also supports the Lighthouse tracking system, known for its accurate and low-latency tracking, thereby catering to the project's need for precise hand movements during medical procedures. Moreover, the Vive Pro 2 is compatible with a wide variety of software development kits, offering flexibility and ease of development.

5.2.3 Choice of 3D Modelling Software

Going into the project, there were no presumptions that a 3D modelling software would be necessary. With no prior experience in professional 3D modelling on the team, the initial thought was to purchase the required models from online artists as it could ensure a certain level of quality and would save time. This idea was strengthened by the discovery of Quixel Bridge [42] – a data bank of free scanned 3D models and materials that can be accessed within the Unreal Engine 5 app, as well as the existence of the Epic Games Marketplace [43] – a market of user-created content, both free and purchasable.

However, as the project developed further, this mindset shifted for a couple of reasons:

1. A MetaHuman [44] would make up the base of the wounded character, while custom clothes were not created with MetaHumans in mind, meaning 3D modelling software would need to be utilized in order for the clothes to inherit the MetaHuman's "Skeleton" [45] and thereby move together with the MetaHuman model.
2. Creating a believable scenario within the simulation is important. This in part means displaying a realistic, bleeding wound. Also, the blood behaviour would need to correspond to real loss of blood, as described in Section 3.2.2. Acquiring models fitting these rather niche specifications were deemed infeasible. As an alternative, employing 3D modelling software to integrate the desired wound could be a more practical approach.
3. There would be less worries about potential copyright issues related to the models, were the simulator to eventually be commercialised.

Downloaded models would still end up as part of the final simulation and things such as grass textures and scanned rocks from Quixel Bridge proved invaluable in creating a realistic environment. However, the clothes for the Metahuman as well as the blood pool forming from the wound be original creations made in a 3D software.

There are a large number of 3D modelling software with different proficiency. Some of the more well-known ones are Blender, ZBrush, Cinema 4D, 3ds Max, Modo and Houdini. Any one of these is capable of not only 3D modeling, but also character rigging and animation - the three intended use cases. The deciding factor therefore came down to the price, ease-of-use for beginners, as well as the availability of useful tutorials and information about the software online. Seeing as Blender was the only free option on this list, with the others having a rather hefty price in the eyes of a private consumer, it immediately became a prime candidate. Since this choice was made so early into the project, there had not yet been a conversation about potentially receiving funds to purchase software or hardware required for the project. There was also no guarantee that the plan to create and use our own models would remain for the length of the project, and as such there was an inherent inclination for us to take a lower risk by using a free software. As for how Blender fulfills the two other factors: While it has a lot of tutorials and other content to aid and inspire users in how to utilize the tool, the learning curve is rather steep. Regardless, we decided to use it with the prospect that if it proved too difficult, we'd simply rely on less optimal models from other users for the current demo, and mark this as future work.

5.2.4 Modelling of a Soldier with a Realistic Wound

Creating a realistic blood simulation posed challenges due to the lack of fluid simulation support in Unreal Engine. An attempt to use a beta-plugin providing water simulation proved insufficient due to its limited customization. Importing animations of Blender's fluid simulations was considered but discarded as it prevented interaction with the scene.

The solution divides the blood simulation into two components: blood flow from the wound, and the resultant blood pool. The flow was modeled using Unreals Niagara Particles system. This approach allowed the blood particles to interact with the scene, ensured the source of particles corresponded to the wound location, and facilitated control over blood flow based on our blood loss model, including halting the flow upon correct tourniquet application. Despite these benefits, the lack of particle interactions and limited physics manipulation upon object collision led to a representation more akin to a spray of particles than a flowing liquid.

5.2.5 Software Design and Optimizations

To meet the high performance targets for the hardware specifications described in Section 5.1.1, the simulator must be resource efficient. This is partially accomplished with the careful choice of a suitable game engine, designed to optimize assets and rendering to be as efficient as possible. However, this doesn't eliminate the need for clever software design. Additionally, poor software design often lead to unnecessarily complex code structures that can be difficult to expand and test. In this section, some of the major design choices that contributed to a comprehensive and efficient software structure will be described.

In Unreal Engine 5, the most common coding interface is the Event Graph, a visual scripting system that allows developers to create gameplay elements, interactive objects, and complex game systems without the necessity of writing conventional code. These graphs essentially provide a canvas for implementing events, functional flow, and logic operations using nodes that represent functions or events. UE5 also offer developers to design their software in regular C++ code, which might be more familiar to seasoned programmers. After an assessment of the two options based on information from experienced UE5 developers, it was decided that all code for this project were to be produced through the Event Graph interface.

While always important to maintain a well organized code structure, this turned out to be of extra high importance when working with the Event Graph. Creation of code in the 2D interface of nodes and connections would quickly grow to chaotic and confusing structures if not carefully designed. By using flow control structures like loops and functions in calculated ways, grouping nodes in visual clusters, and creating descriptive comments, a clear code structure could be maintained. This made the event graphs easy to debug and redesign.

In order to guarantee the optimal performance of the software, algorithms were designed with run-time efficiency in mind. Computational structures such as nested loops, which are essentially loops inside of other loops, can easily lead to an exponential increase in the computation time, particularly if the data set is large. By avoiding such structures, the software would not only run better, but also allow for more future expansion without suffering from performance losses.

5.2.6 Using a Skybox to Improve Performance and Immersion

In early sprints, a landscape of a vast grassland covered with trees was developed to mimic a sparsely vegetated southern-Swedish forest with the intention to make this the environment of the simulator. Using the advanced landscape sculpting and model populating tools provided by UE5, the team quickly designed an extensive natural world. However, due to the high number of high-resolution 3D objects in the world, performance issues arose. Various attempts to counter these issues, such as decreasing texture resolutions and the number of objects, failed to solve the problem while maintaining the desired realism. Further, not only did the expansive world impact the software performance, but it also made re-adapting the simulator for other environments significantly more time-consuming.

Seeking an alternative, the team drew inspiration from a common strategy in video game design: the use of *skyboxes* [46]. Skyboxes, textures within a large or infinite sphere, are commonly used to create the illusion of an expansive environment, effectively circumventing performance issues associated with rendering distant objects like clouds or stars.

Figure 5.1: The setting is a typical Swedish countryside. The nearby rocks and grass terrain are part of the level, while the distant houses, fields and forests are part of the skybox.

The feasibility of replacing objects with a skybox primarily relies on the relation between in-game movement and distance to the distant objects. Parallax effects are impossible (or difficult) to implement for skybox "objects", so the player must be confined into a small enough space that from their perspective, any parallax caused from moving around would be negligable for objects as far away as the skybox objects. This turned out to be a perfect solution in the case of this training simulator, since it only employs a playable area of a few square meters.

5.3 Final Prototype

This section provides a detailed view of the final simulator prototype for combat casualty care training. The intent is to describe the functionality and showcase the simulator design and environment.

5.3.1 Environment and Setting

The developed prototype is a VR simulator encapsulating a single level. The basis of the chosen environment is a 50 by 50-meter grass field, displaying varied topography and adorned with boulder and slab 3D models to accentuate the natural ambiance. This terrain, while designed with finite dimensions, appears expansive and virtually limitless, owing to the integration of a 360-degree image of Swedish countryside, captured with a drone and positioned in the VR scene as a skybox. As the user navigates within this VR world, they witness distant trees and houses, imparting a semblance of reality to the virtual environment.

Figure 5.2: A MetaHuman, dressed with Swedish tactical clothing makes up the virtual soldier. The soldier roughly mimics the movement of a real person or doll based on the positioning of four Vive Trackers.

5.3.2 Character and Interaction

At the beginning of a simulation, the trainee finds themselves adjacent to a wounded soldier, whose virtual location is tracked using four HTC Vive Tracker 3.0 devices. These trackers, strategically connected to the soldier's hands and feet, can, in reality, be assigned to either a human or a doll. This adaptability permits the simulation to correctly exhibit the weight and physical characteristics of the virtual soldier.

The virtual soldier, depicted in Figure 5.2, roughly resembles a generic officer of the Swedish Armed Forces. Modelled around a MetaHuman, the male soldier has jacket and field trousers, and accompanying combat vest, boots and helmet. The colour patterns of the clothes are based on the Swedish M90 camouflage and uniform.

5.3.3 Audio-Visual Effects and User Experience

The environment exudes an atmosphere of war, with sound effects of gunfire, war machines, and explosions punctuating the ambient silence. These effects contribute to the overall immersion and challenge of the simulation, encouraging the user to strategically maneuver the wounded soldier. A particularly loud cluster of gunfire emanates from the vicinity of a nearby boulder, signalling an exposed position. The user's objective becomes clear: relocate the wounded soldier to a safer location, behind the boulder, before initiating medical treatment. The use of tracking technology ensures a realistic relocation process, challenging the user's tactical acumen and physical abilities.

Figure 5.3: The wounded soldier is exposed to the general direction of gunfire. The trainee must strategically relocate his virtual comrade to safety behind the boulder before proceeding with medical care.

5.3.4 Interactive Props

The simulation incorporates a physical tourniquet that the user can apply to the wounded soldier. Once applied successfully, an external training instructor, observing the simulation, can halt the virtual bleeding by activating a keyboard command on the computer running the simulation.

5.3.5 Performance and User Comfort

Performance optimization was a key focus throughout the development process. The application can run with a frame rate above 90 FPS, for most of the time, but suffers from occasional drops resulting in momentarily frozen frames or stutter. With the short training scenario used these performance issues don't introduce motion sickness, but can cause brief disorientation for the user. This, however, is not solely a product of the software itself, but partially due to poor tracking. Provided that the external tracking lighthouses are set up correctly, and a adequately equipped computer system is used, the simulator runs at acceptable levels.

5.4 Feedback from Demonstrations

Three demonstration sessions were arranged to evaluate the strengths and potential areas for improvement in the solution.

The first demonstration took place two sprints before the set deadline for development and was formatted as a presentation before a group of students. The session focused on broader aspects of the solution, inviting comments on the visual presentation, the concept, and its potential applicability in a learning context. Feedback from this session was considered during the final two sprints, contributing to the finalizing of the software.

Upon the completion of the prototype, the other two demonstrations were arranged. These involved participants with medical knowledge who interacted directly with the simulator. This hands-on approach offered critical perspectives on usability, realism, and pedagogical effectiveness. The participants' feedback, given their understanding of the medical procedures simulated in the system, was particularly valuable.

5.4.1 First Interactive Demonstration

During the first interactive demonstration, medical personnel identified several strengths and weaknesses with the prototype. Positive feedback included:

- The graphical representation of a Swedish landscape was described as realistic.
- The audio provided a realistic and immersive battlefield experience, albeit with a somewhat low volume.
- The weight of the HMD was not perceived as a problem but rather as a realistic substitute for a helmet and other head-mounted equipment in a real combat scenario.

Constructive feedback included:

- The cord between the HMD and computer may get tangled in complex medical procedures that require moving around the casualty.
- The positioning of the virtual soldier and the physical training partner were not adequately aligned for a seamless interaction.
- The tracker mounted on the wounded arm obstructed a seamless application of the tourniquet.

Most notably, the participants reported difficulties with executing actions in the real world while fully immersed in the VR environment. Specifically, accessing the medical bag and applying the tourniquet proved challenging due to the lack of real-world visual feedback. To overcome this hurdle, the suggestion was made to incorporate a passthrough feature using the built-in camera(s) of the HMD. This feedback led to adjustments to the prototype, introducing translucent passthrough functionality that allows the user to see both the virtual world and their physical surroundings simultaneously.

5.4.2 Second Interactive Demonstration

The second interactive demonstration was conducted with a former Medical Captain of the Swedish Marine. The session was divided into two parts: with and without the translucent passthrough feature. The feedback was largely in line with that

Figure 5.4: A medically trained participant of the first interactive demo tests the simulator using a HMD. A member of the project group acts as the wounded soldier, tracked with Vive Trackers on their wrists and ankles.

received during the first interactive demonstration. However, the captain identified additional strengths and limitations, including:

- The virtual soldier accurately resembled officers of the Swedish Armed Forces.
- When the passthrough feature was activated, the virtual soldier was found to be misaligned with the body parts visible through the cameras.
- The simulated wound, while realistic, did not appear suitable for tourniquet application but seemed better treated with a pressure bandage.

Having prior experience with civilian medical MR training applications, the captain confirmed that the misalignment of physical assets and their virtual counterparts is a common issue in related fields.

6

Discussion

The discussion involves an examination of the methods and approaches used and how effective they were in developing and evaluating a prototype. Following that, an in-depth evaluation of the prototype's strengths and weaknesses. Lastly, the potential for future improvements will be explored, highlighting the areas where the simulator could be further refined or expanded. The aim is to provide a comprehensive understanding of the implications of the research and to establish a basis for further work in this rapidly evolving field.

6.1 Method and Approach

Structuring the project to follow the principles of Design Research Methodology and formatting the work in accordance with the basics of Agile product development were of great value and allowed the development to proceed with continuous feedback. The cyclic iterations of the DRM stages provided a good baseline for the research of this thesis. That said, the project was undertaken with an open-ended and exploratory approach, with an emphasis on adaptation for changing circumstances. The absence of a rigid structure allowed the project to evolve organically based on the emergent needs and insights gathered during development.

The methodology was not without its challenges. The absence of workflow utilities, such as version control and a unified collaboration solution, sometimes led to difficulties in managing progresses. A variety of alternative solutions were applied, including manual backups, Cloud-based sharing and other file sharing systems, which sometimes caused confusion in navigating versions and storage locations. Despite these challenges, the team was able to make use of the flexibility inherent in this method and could adapt solutions after circumstances and needs.

6.2 Evaluation

This thesis attempts to evaluate if a MR simulator can serve as a potential solution to improve the effectiveness of combat casualty care training. In this section, the findings and outcomes of the thesis will be evaluated and discussed in regard to how effectively they answer the research questions.

6.2.1 What are the barriers towards achieving a quality, effective and good-practice VR training in tactical care?

Creating a realistic environment using VR while maintaining the physical interaction with tools and medical equipment proved to be one of the bigger barriers. The hand controllers that come with most VR systems fail to incorporate the dexterity associated with medical care. The proposed prototype attempts to solve this by integrating physical objects and removing the hand controllers from the interface, but fail to do so in an intuitive and seamless manner.

One challenge identified during the evaluation was the alignment between the physical training partner and the virtual soldier. Deviations in their positioning can disrupt the immersion and the training process, as the trainee has to mentally adjust their actions to align with both the physical and the virtual realities.

In terms of the pedagogical aspect, the evaluation showed that the simulator successfully engages trainees and presents them with a realistic and challenging scenario. However, the current implementation does not completely mirror real-world dynamics. For instance, the application of a tourniquet on the simulated wound was not completely in line with standard medical procedures.

6.2.2 How can digital and physical assets be combined in MR training for tactical care, and how can we measure success?

The combination of digital and physical assets in mixed reality creates a hybrid environment where trainees can interact with physical objects while immersed in a stressful simulated scenario. The physical component is crucial for skills that need tactile feedback.

On the technical side, the graphical representation of the environment and the virtual soldier were praised for their realism. This highlights the potential of VR technology to accurately mimic real-world environments and scenarios, offering an immersive training experience. Audio was another key contributor to the immersion of the simulator. Feedback regarding the sound effects confirmed that they effectively created a battlefield atmosphere, which is essential for military training.

In regard to cost-effectiveness, XR training simulators have shown great potential in many fields prior and seem capable of significant cost reductions for tactical and first-responder training too. Traditional training methods require significant logistical arrangements and often incorporate expensive training equipment and personnel. XR training systems provide inexpensive, scalable solutions that can allow for easy adjustments to suit the needs for a specific training programme.

A continuous dialogue and regular meetings with people trained in tactical care proved to be of great value in evaluating the prototype and its development. The demonstrative sessions of the final prototype also gave much clarity in its strengths and weaknesses.

To further improve the measurement of success, it would have been helpful to have longer demonstrations in cooperation with armed forces, where soldiers could thoroughly test and evaluate the prototype. A more elaborate study could attempt to compare performance of trainees in tests before and after the MR training. This was however out of scope for this thesis.

Ultimately, the goal of the training is to improve outcomes in real tactical care situations. Tracking these outcomes over time and comparing them to those before the MR training was implemented can provide a measure of the training's overall success. This, of course, requires years of real-world deployment and data analysis.

6.2.3 What can be learned from applying MR training to tactical care?

The field of medical XR training research still lacks a thorough assessment of how physical and digital assets can be combined in an intuitive manner in MR training simulators. It is clear that more research in this field can benefit the development of future medical MR training simulators.

The testing of the prototype highlights areas that need improvement to create a comprehensive and effective XR training simulator. The prototype does however show promise, and there doesn't seem to be any major barriers towards a more refined simulator that addresses the current problems. Furthermore, as VR and MR technologies continue to develop, new systems will allow for better interaction.

6.3 Future Improvements

This section discusses what we believe future researchers can do that we were not able to accomplish, and elaborates on potential approaches for achieving this.

6.3.1 Passthrough

The utilization of passthrough technology in the final prototype was introduced at a late stage, leaving insufficient time for iterative improvements based on user feedback. Future research endeavors should allocate considerable time to explore additional passthrough solutions in various projects and examine how different levels of passthrough impact simulation outcomes and user perceptions. This investigation should aim to determine an optimal passthrough percentage that strikes a balance between the immersive qualities of the simulated world and the authenticity of reality, allowing each element to complement rather than overshadow the other.

Another intriguing avenue for exploration is targeted passthrough, whereby the passthrough effect is applied selectively to specific areas of the user's view. Integrating this approach into the virtual reality (VR) solution may provide the ideal fusion of experiences. By perceiving the tactical scenario within the simulated world and observing the graphical representation of a wounded individual directly ahead, users can concurrently maintain visual awareness of their own hands and tools through a small window strategically positioned to align with the typical hand placement during fine motor skill practice.

6.3.2 Improvements for Virtual Human

The research and analysis on incorporating a virtual human (VH) to simulate the role of a casualty yielded promising results; however, several suggested features were either missing or implemented inadequately in the final prototype, hampering comprehensive evaluation. One notable absence was the lack of an emotional response system, which could have been programmed to activate at timed intervals to simulate various symptoms of hypovolemic shock. Furthermore, the body-tracking mechanism encountered accuracy issues, resulting in the VH rendering incorrectly in relation to the trainee. These challenges can be addressed by employing improved tracking equipment and leveraging the existing muscle features of the Metahuman avatar model to animate emotional responses.

As discussed in Section 5.2.4, the blood animation for the wounds consisted of two distinct elements: a particle stream representing bleeding and an expanding cylinder simulating a blood pool. However, one limitation of this approach was the fixed location of the blood pool, hindering the formation of new puddles when the casualty is moved. To achieve a more ideal solution, a functional liquid simulation capable of realistically modeling blood flow without such constraints would be advantageous. Nevertheless, developing such a simulation within the Unreal Engine presents challenges due to the limited tools available for this purpose. Additionally, the computational demands associated with fluid simulations need to be addressed, considering the significance of stable high frame rates in virtual reality (VR) environments, which further exacerbates the complexity of the task.

6.3.3 More Environments

Expanding the repertoire of simulated environments for training purposes holds considerable potential for enhancing the simulator's applicability across various professions, such as police or security guards, thereby increasing its relevance and broadening its user base. Introducing diverse environments, including cityscapes and different terrains, would render the simulator more relatable to these professions, enabling trainees to practice in settings that align more closely with their real-world operational contexts. This extension would naturally incorporate specific cautions and hazards pertinent to these new environments, effectively preparing users to be vigilant and proactive in identifying potential dangers. Moreover, the inclusion of varied environments serves a broader purpose by promoting unpredictability, thereby mitigating the development of training scars and fostering adaptability in trainees.

6.3.4 More Types of Care

To provide a comprehensive and well-rounded training program, it is imperative to incorporate the remaining care procedures outlined by the Tactical Combat Casualty Care (TCCC) guidelines. Including scenarios with diverse levels of emergency for the wounded individuals offers several advantages. Firstly, it expands the trainees' knowledge base and technical proficiency, enabling them to handle a wider range of medical situations effectively. Additionally, such scenarios introduce heightened decision-making and strategic thinking requirements, further enhancing the trainees' ability to make critical judgments under pressure. Consequently, the overall quality of the trainees' performance is likely to experience significant improvement.

6.3.5 Post-training Results and Feedback

Enabling trainees and mentors to retrospectively analyze previously simulated scenarios would yield significant benefits. By accessing detailed information such as the duration of care application, applied pressure in tourniquets, and correct casualty handling, both trainees and mentors can leverage concrete data to enhance performance evaluation and feedback. Moreover, this retrospective analysis facilitates the identification of individual strengths and weaknesses within training divisions, allowing for broader investigations into educational disparities and related findings.

Tracking the pressure exerted by a tourniquet could be addressed through the utilization of a Bluetooth-connected pressure sensor. By incorporating it into the tourniquet, it becomes possible to detect the pressure between the tourniquet and the casualty's limb. This real-time pressure data could then be transmitted to the computer system, serving two crucial purposes. Firstly, it can be employed to dynamically control the blood flow simulation, enhancing the realism and accuracy of the training experience. Secondly, the data can be stored for subsequent analysis, enabling in-depth examination of each simulated scenario.

7

Conclusion

The military and first responder sectors consistently seek quality, cost-effective solutions for emergency medical training. XR has emerged as a promising avenue, offering advantages such as low-cost, easy deployment, and the capability to simulate a broad range of scenarios. In fact, in many instances, XR has proven superior to traditional methods in fostering decision-making skills and readiness to act. Its successful application in adjacent fields, like civil medical training, further underscores its potential.

However, while the benefits of XR are evident, its application in the realm of more technical care teaching is still a developing area. Whether it's small-scale prototypes created by educational institutions or large-budget initiatives backed by the military, XR solutions have yet to fully leverage the practical, hands-on aspects of traditional training. This observation does not diminish the potential of XR solutions, but rather highlights an area for further exploration and refinement. This project aims to contribute to this evolving field, striving to infuse realism and immersion into the virtual training landscape while preserving the inherent value of hands-on practice.

This thesis reflects on previous work and solutions in the field, to identify potential pitfalls of developing an XR application for tactical care training. Promising techniques and methods to solve the problem were evaluated and the findings documented. This was done through incorporating them into a low-fidelity prototype that was regularly tested throughout the project by a group of people with tactical care training. Based on their feedback, the concept was iteratively improved upon.

Several challenges were encountered during the project. Notably, the accurate tracking of physical objects and aligning them with their virtual counterparts posed a considerable challenge. However, these challenges were crucial learning points, offering valuable insights into the complexities of developing an MR solution that seamlessly combines virtual and physical elements.

While the prototype demonstrates the potential of MR for tactical care training, it also points to future areas of research and development. Better integration of physical and virtual elements, and expanding the range of interactive medical gear are promising avenues for future work.

In conclusion, this project contributes valuable insights and a promising prototype to the growing field of XR training research. It signifies a step towards a future where MR could potentially complement traditional hands-on practice, offering a flexible, scalable, and immersive training solution for emergency medical care in military and first responder contexts.

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