BellatorVR: A Virtual Reality Application to Support Firearms Training for Military Police

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Abstract. *This paper presents BellatorVR, a virtual reality application designed to support firearms training, particularly by mitigating risks associated with live weapon use for novice users. The system offers a controlled and immersive environment for realistic weapon handling and tactical practice. Its development included optimized 3D modeling, interaction mechanics, and design patterns to ensure performance and usability. An exploratory pilot study with four participants was conducted to assess feasibility, user interaction, and initial perception. Preliminary feedback indicates that BellatorVR shows potential as a complementary tool for early-stage training, providing valuable insights to guide future development.*

1. Introduction

Virtual Reality (VR) has revolutionized several fields, particularly in healthcare, flight simulation, architecture, and military training. By immersing users in interactive three-dimensional environments, VR enables realistic sensory simulations through the integration of haptic, visual, and auditory feedback. Its concept is grounded in the creation of a virtual environment perceived as real by the user. Thus, the significant impact of Virtual Reality lies in its ability to offer greater safety and efficiency in modern, high-risk work environments [Brown et al. 2021, Jerald 2015].

From this perspective, adequate combat training is fundamental in preparing security agents to face situations that demand both physical and psychological skills. It is essential for preventing accidents and for ensuring the safety of both military police officers and society at large. Traditionally, this formative process involves theoretical instruction and practical exercises with physical simulations, which are often limited by safety constraints [CTTPE 2023]. Building upon this, firearms training requires the acquisition of technical skills while also exposing recruits to emotional strain, particularly during their first contact with real weapons [Ningeliski 2024]. In this context, VR serves as an effective complementary tool, offering a safe and immersive environment in which recruits can become familiar with weapon handling and develop appropriate responses to critical situations without physical risk.

Military police officers are exposed to potentially traumatic events (PTEs) more frequently than the general population, due to the inherent responsibility of handling dangerous equipment and the constant pressure to make rapid decisions in high-stress situations. These factors contribute to psychological strain, making officers more susceptible to developing post-traumatic stress disorder (PTSD) [Jerald 2015, Jorgensen and Elklit 2021].

For this reason, this paper introduces BellatorVR, a virtual reality application developed to support firearms training for Brazilian military police officers. The system provides a controlled virtual environment to ensure a safer and more effective learning process for handling firearms, especially by minimizing the emotional impact often experienced by recruits when dealing with weapons for the first time. The use of VR in training scenarios has been shown to offer safe learning environments that would otherwise be hazardous. This approach contributes to reducing PTSD by gradually increasing exposure to feared stimuli, which differs from traditional training systems [Lee et al. 2015].

This study constitutes an exploratory pilot investigation, conducted with a small group of four police officers from the 2nd Military Police Battalion of Caxias, Maranhão, to evaluate the feasibility, acceptance, and preliminary effectiveness of BellatorVR in a real-world training context. The primary goal of this study is to explore the system's practical feasibility and user reception in a real-world context, providing valuable insights that will shape future developments and broader evaluation studies.

The following sections detail the development pipeline of BellatorVR, its architecture choices, interactive mechanics and initial user feedback collected during field testing.

2. Related Works

In the military field, virtual reality (VR) has become increasingly integrated into military and police training worldwide, offering immersive environments that reduce risks and increase the repeatability of critical scenarios. However, many of these solutions, though advanced, present limitations when considered from the perspective of accessibility and suitability for novice training in Brazilian law enforcement contexts.

Several international platforms, such as Apex Officer in the United States, provide law enforcement with realistic tactical VR simulations. These platforms are often equipped with motion tracking and branching scenarios for use-of-force decision-making [Rocha 2022]. However, these systems tend to be proprietary, expensive, and designed around U.S. protocols, weapon types, and legal frameworks. This limits their applicability in countries like Brazil, where training standards and field realities differ significantly.

In Brazil, some initiatives have emerged in recent years. For instance, BM Verso, developed by university students at UniRitter and adopted by the Military Police of Rio Grande do Sul, uses VR to simulate urban patrol scenarios [Governo do Estado do Rio Grande do Sul 2023]. Similarly, the Military Police of Santa Catarina employs simulation tools for training firearm use and critical incident response [Rosa and Pavanati 2014]. Although promising, these tools are often used in isolated pilot programs, with limited public documentation, low scalability, and unclear alignment with national training standards.

Moreover, many existing VR solutions assume a baseline level of firearm familiarity, making them less suitable for recruits experiencing their first contact with a weapon. Most do not offer progressive training mechanisms or safeguards to reduce cognitive overload and emotional distress during early learning phases.

Finally, high-end VR systems often require dedicated facilities, tethered hardware, and substantial investment in infrastructure, which can be a significant barrier for public security agencies with limited budgets. This economic constraint is especially relevant in the Brazilian context, where cost-effective and scalable training tools are essential. BellatorVR was designed with this reality in mind, prioritizing the use of standalone headsets such as the Meta Quest 3, which eliminate the need for external computers or tracking systems, significantly reducing the cost of adoption and making the system more accessible to institutions with limited resources.3. Pipeline

BellatorVR was developed for the Meta Quest 3, a standalone VR headset by Meta. To ensure compatibility and performance, the Unity engine was used to build the virtual environment and interactions, with C# scripts implemented via Visual Studio Code.

Additionally, Blender was used for 3D modeling, rigging, and UV unwrapping, following a low-poly approach optimized for real-time use. Texturing was done in Adobe Substance 3D Painter, using physically based materials (metalness, roughness, wood) and texture baking to balance visual quality and performance.

3.1. Procedures for 3D Object Modeling, Texturing, and Rigging

This section presents the 3D modeling of the objects used in BellatorVR, including the modeling, UV mapping, and texturing stages. These steps were developed with a focus on optimization and realism, taking into account the requirements of the virtual environment. The same techniques were applied across different objects, ensuring both visual and technical consistency. Figure 1 illustrates the general workflow used in the 3D asset creation process, including conditional paths for specific cases such as the hand and weapon models.

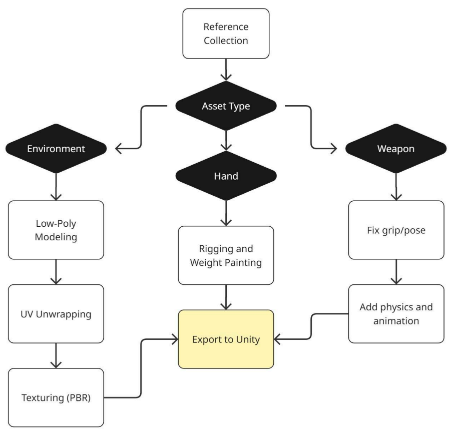
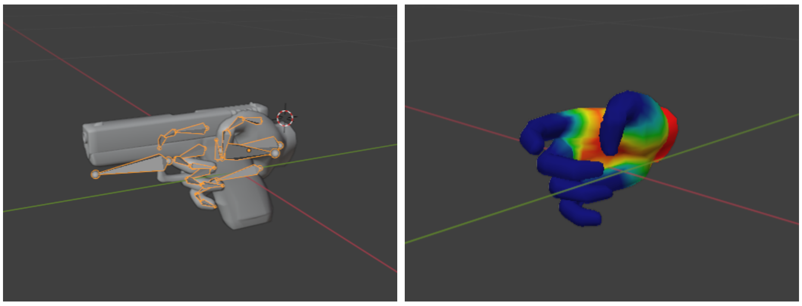


Figure 1. Flowchart of the 3D asset modeling and integration process.

3.1.1. Construction and Adjustment of the Hand for Realistic Interactivity

The rigging process was applied to animate weapon hand gripping. This process involves creating a skeletal structure within the 3D model, allowing it to move realistically. Rigging was essential to ensure the hand deforms correctly when holding the firearm. Using Blender, bones were added for each finger, as well as the palm and wrist, enabling individual movement of each part (Figure 2(*i*)). This configuration allowed for detailed manipulation of the hand, which was crucial to ensure that the fingers adjusted precisely to the shape of the weapon.

Subsequently, the Weight Painting technique was applied to assign bone influences to the vertices of the modeled hand, over the base mesh provided by the XR Interaction Toolkit. The vertex weights were gradually adjusted around the finger joints to ensure smooth transitions between different parts of the hand. This step was essential to prevent unwanted deformations during animation (Figure 2(*ii*)).



(*i*) (*ii*)

Figure 2. Hand Rigging and Weight Painting: (i) Bone rigging for realistic weapon grip, (ii) Vertex influence distribution on the hand mesh.

For the grip animation, each finger was positioned to replicate the natural mechanics of a real hand holding a firearm. The index finger was aligned with the trigger, while the middle, ring, and little fingers were configured to wrap anatomically around the weapon's grip. The thumb was placed along the side to provide additional support, as in a realistic holding posture (Figure 3). The movement was tested to ensure proper adjustment of the fingers to the weapon's curves and surfaces.

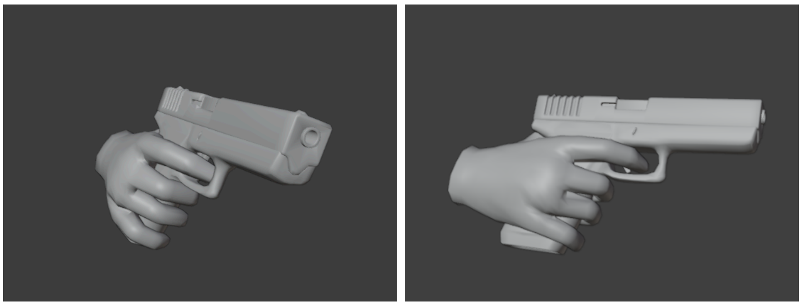


Figure 3. Hand rigging configuration and grip positioning on the weapon.

All these processes collectively ensured that the interaction between the hand and the weapon was both functional and visually convincing, meeting the realism and precision requirements essential for the application.

3.1.2. Virtual Environment Modeling and Construction

As previously stated, the initial modeling was carried out using Blender. The process began with the definition of the object's basic shapes, using geometric primitives such as cubes and planes. From these initial forms, detailed adjustments were made to add specific features, such as table legs and the lower panel. As an example, the modeling and texturing process of the environment is described below and illustrated in Figure 4. The development aimed to balance visual realism with performance optimization for real-time environments. The stages are summarized as follows: (*i*) modeling – base shapes defined and refined with structural details; (*ii*) topology – low-poly mesh optimized for virtual use, shown with wireframe to illustrate polygon distribution; (*iii*) UV mapping – unwrapped layout minimizing distortion and maximizing texture coverage; (*iv*) texturing – application of realistic materials (wood, metal, plastic) adapted to object function.

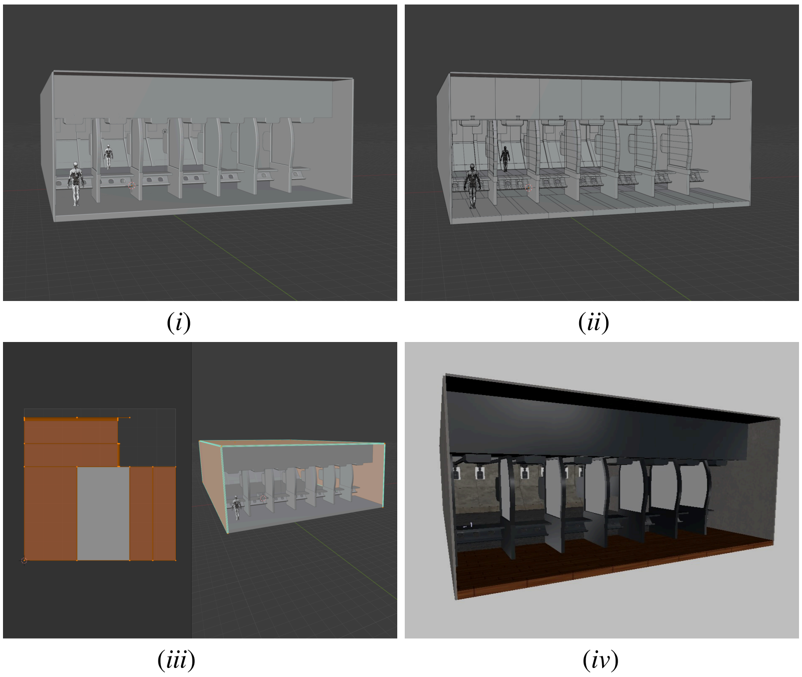


Figure 4. Scene modeling and texturing: (i) 3D model of the environment, (ii) Model with wireframe enabled, (iii) Unwrapped UV map, (iv) Textured scene.

Although the previous example detailed the process applied to the overall scene modeling, the same workflow was followed for each individual object used in BellatorVR. All models went through the same stages of modeling, UV unwrapping and texturing, which ensured consistency in both visual quality and technical structure, regardless of their complexity or functional role.

In addition to the manually created models, BellatorVR incorporated a firearm model sourced from CGTrader, originally created by Wyreframe (2020) and used in accordance with licensing guidelines. The asset was reviewed and adjusted to ensure appropriate topology and visual consistency within the virtual environment, as shown in Figure 5.

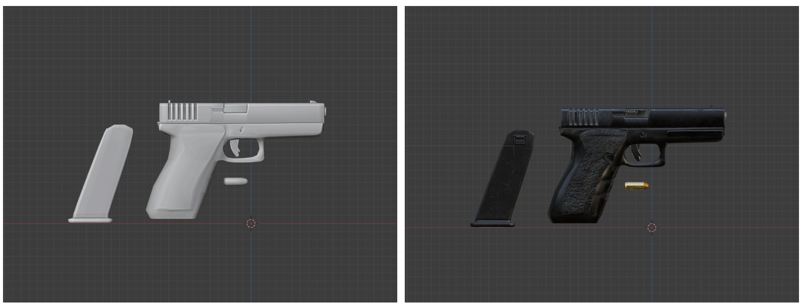


Figure 5. Glock Model Overview by Wyreframe.

This strategy was adopted to streamline the production pipeline and allowed the development team to focus on other critical stages of the project, while maintaining compliance with licensing and ethical research practices.

3.1.3 Look Development

The Look Development phase is a critical stage in the 3D production pipeline, responsible for defining and refining the visual appearance of models and scenes. Initially, the environment presented a simplified visual state, as shown in Figure 6. This phase was therefore essential to enhance the visual quality of the 3D assets and achieve a realistic aesthetic. The process involved configuring materials, adjusting lighting, applying textures, and implementing light baking techniques to balance visual fidelity and performance in the virtual environment.

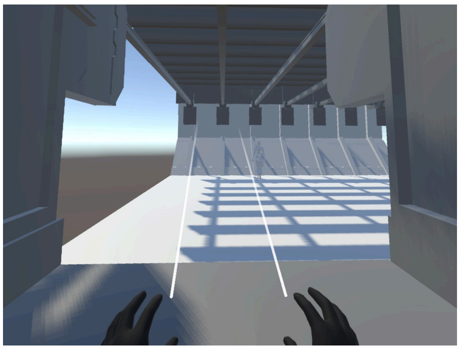


Figure 6. Environment before Look Development.

To achieve realism, materials were configured with custom shaders, ensuring that metallic, plastic, and concrete surfaces exhibited accurate physical properties. Shaders are small programs that define how light interacts with surfaces, and were fine-tuned during this stage. The metallic shader, for instance, was adjusted with specific parameters for roughness and specularity to produce natural reflections and precise lighting responses.

In addition, light baking was applied to optimize performance without compromising visual quality. This technique precomputes lighting and shadow data into textures or lightmaps, significantly reducing the computational load during real-time rendering. The baked lightmaps were generated based on material properties and the position of light sources, ensuring soft and natural shadows throughout the environment.

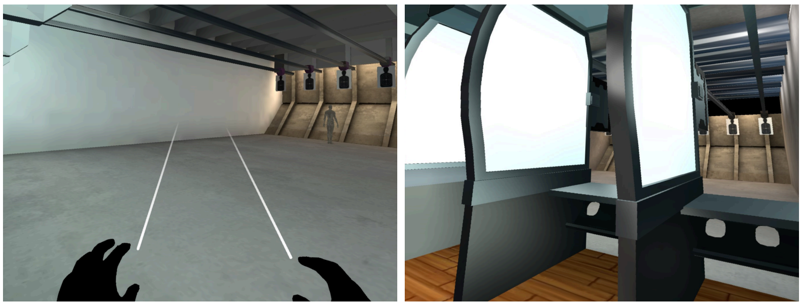


Figure 7. Environment overview from multiple perspectives.

As shown in Figure 7, the final result of the Look Development phase was a visually coherent scene, featuring well-distributed lighting, detailed materials, and improved performance. These results were achieved through the combination of optimized lighting techniques, texture refinement, and shader configuration, contributing to an immersive and aesthetically pleasing virtual experience.

3.2. Virtual Environment Modeling, Construction and User Interactions

The initial step in this section involved configuring the Unity environment to recognize motion controllers as virtual hands using the XR Interaction Toolkit. Traditional VR controllers were replaced with 3D hand models, enabling the system to represent user hands in the virtual space. Afterwards, dynamic interactions were added through real-time animations that responded to controller inputs. These included Trigger (index finger movement) and Grip (closing the fist) actions.

As shown in Figure 8, both the initial static hand representation and the responsive hand animations are illustrated, demonstrating the integration and real-time functionality of the virtual hand controls.

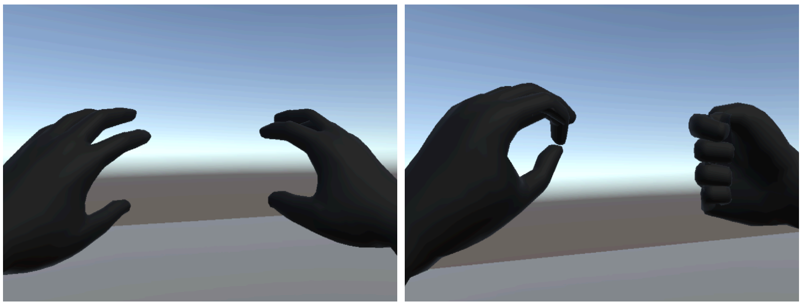


Figure 8. Hand Interaction Setup in Unity.

Following the initial integration of the motion controllers and the implementation of Trigger and Grip animations, the next stage focused on expanding interaction with virtual objects to enhance realism and user immersion. The development included advanced mechanics to simulate physical interactions within the environment.

The implemented system was based on Raycasting, where a virtual beam is projected from each hand to detect interactable objects. This beam is visually represented and provides directional input for selection and manipulation, as shown in Figure 9.

The stages are summarized as follows: (*i*) Raycast Setup – a visible beam originating from the user's hand indicates the direction of interaction and highlights the target object in the scene; (*ii*) Object Grip – upon pressing the controller's grip button, the highlighted object is selected and can be moved freely, simulating real-world grabbing mechanics; (*iii*) Dual Interaction – the system supports simultaneous manipulation of two separate objects, one in each hand, increasing the interaction complexity and realism; (*iv*) Physics Implementation – using Unity’s Rigidbody and Collider components, objects were given physical properties such as mass, gravity, and collision detection. Stacked cubes illustrate the stable interaction enabled by this setup.

Figure 9 demonstrates the evolution of virtual object manipulation, from selection and grabbing to dual-hand interaction and physics-based behavior.

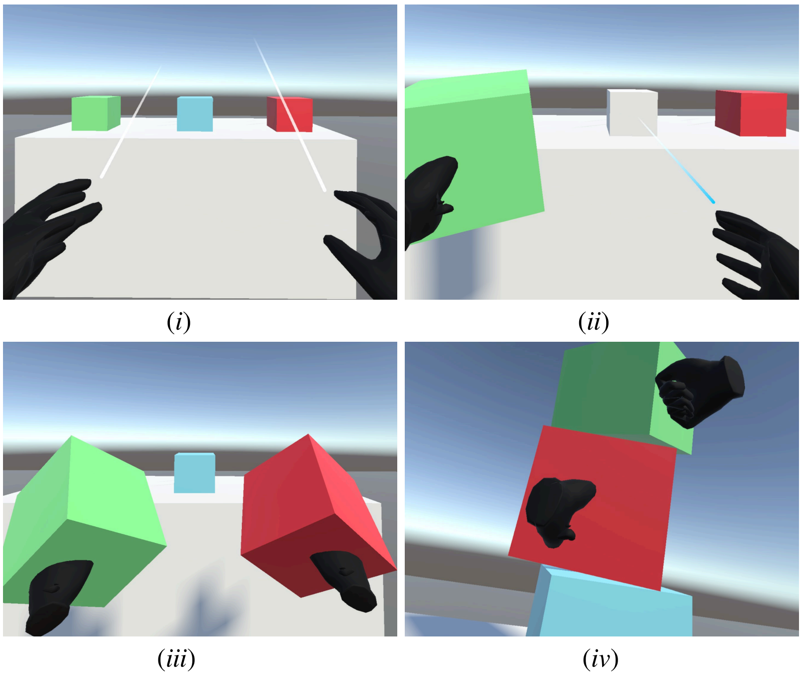


Figure 9. Interaction with virtual objects.

The colored cubes were replaced with the Glock model by Wyreframe (2020) to evaluate object interaction in a more realistic context (Figure 10).

Figure 10. Firearm manipulation test.

However, the initial integration revealed misalignment issues between the hand and the weapon, resulting in an unnatural and offset grip. These inconsistencies highlighted the need for refinements in the rigging system and grip point configuration to ensure a more natural and responsive interaction. Consequently, the procedures described in Section 3.1.1, were applied to address these challenges.

3.3. State Machine for Weapon Management

The architecture of BellatorVR was designed with a focus on performance and immersion, prioritizing a smooth, uninterrupted user experience throughout the virtual simulation. To achieve this, the weapon system was developed using a handling mechanic structured around two software design patterns: Finite State Machine and Command Pattern, enabling consistent behavior and scalable interaction logic.

• **Reloaded**: This state indicates that the weapon is loaded and ready to fire. It serves as the initial point in the weapon's operational cycle and is triggered when the cartridge comes into contact with the weapon.

• **Shooting**: This state is activated during the firing action, provided the weapon is loaded. It simulates the behavior of a shot, and upon completion, the logic evaluates whether ammunition is still available to transition back to the reloading state.

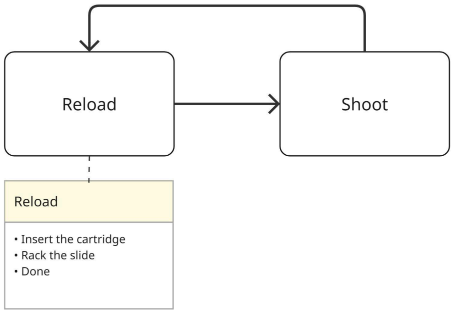


Figure 11. Finite State Machine and Commands Pattern Flowchart.

Regarding the Commands Pattern, each user action was encapsulated into independent command classes, improving code modularity and reusability instead of relying on direct function calls (Figure 11).

Transitions between these states are managed using the SwichState() method, which calls Exit() on the current state and Enter() on the next, ensuring separation of concerns and maintainability. A simplified pseudocode representation is presented below:

```
States: Reloaded, Shooting
CurrentState ← Reloaded

loop:
    CurrentState.Update()

method SwichState(nextState):
    CurrentState.Exit()
    CurrentState ← nextState
    CurrentState.Enter()
```

Figure 12. Weapon state machine pseudocode.

A practical evaluation of user interaction with the firearm was also conducted. As shown in Figure 13, this testing phase assessed grip accuracy, controller responsiveness, and the execution of shooting and reloading actions. It also verified whether state transitions within the State Machine operated correctly, ensuring natural and intuitive feedback during use.

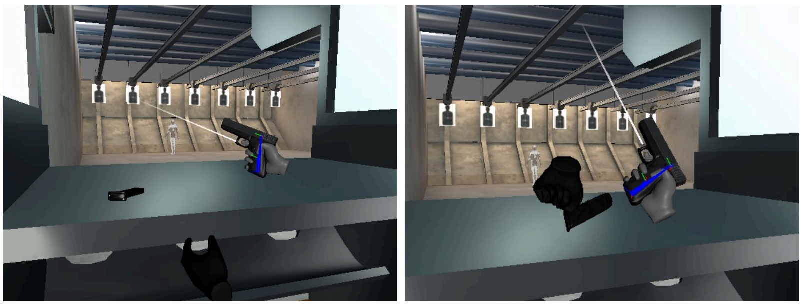


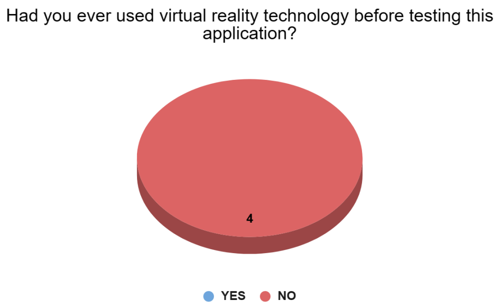
Figure 13. Reload and magazine handling test in the BellatorVR.

The input system in BellatorVR was configured to provide intuitive and realistic interaction within the virtual environment. The control mechanics are structured as follows: (*i*) left joystick – enables player movement (forward, backward, and lateral); (*ii*) right joystick – controls camera rotation without requiring physical body movement; (*iii*) trigger button – used to fire the weapon when pressed; (*iv*) grip button – allows users to hold and interact with objects or weapons while pressed; (*v*) lower buttons (X and B) – eject the magazine to enable reloading.

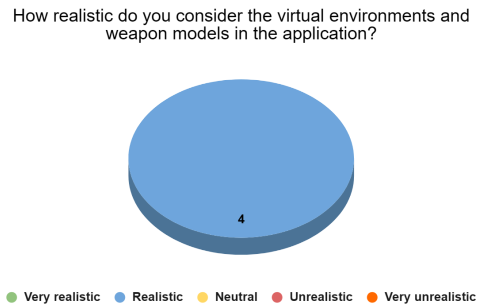
These mechanics ensure smooth and responsive control, allowing the user to efficiently perform all necessary actions for weapon handling and navigation within the virtual environment.

4. Results and Discussion

The data collected from four participants provided initial insights into user interaction with the BellatorVR simulator. As summarized in Figure 14: (*i*) none of the participants had prior experience with virtual reality, highlighting the importance of intuitive controls and a user-friendly interface; (*ii*) all four participants described the virtual environments and weapon models as realistic, suggesting that the 3D modeling, lighting, and material design contributed positively to immersion; (*iii*) three participants reported being satisfied with the system, while one reported being very satisfied, indicating a generally positive user experience and (*iv*) all four stated they would recommend the simulator to others, reflecting a favorable initial impression of VR as a complementary training tool.



(*i*)



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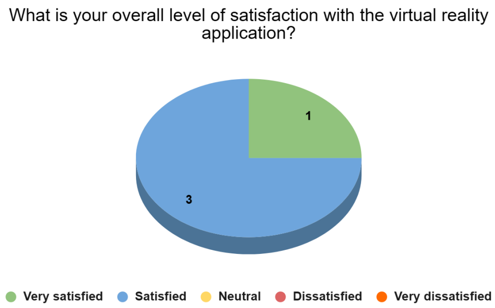

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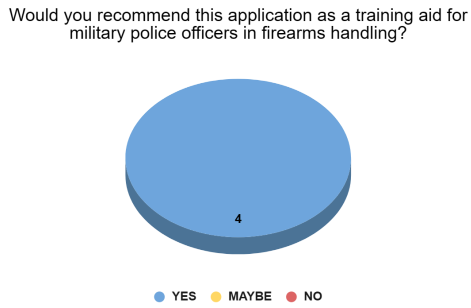

(*iv*)

Figure 14. User Feedback on BellatorVR: Experience, Realism, Satisfaction, and Recommendation.

Despite the small sample size, the feedback gathered reflects meaningful perceptions regarding the usability and realism of the system. During testing, participants demonstrated high levels of engagement and expressed that VR-based training represents a promising alternative to traditional methods. No discomfort or adverse symptoms were reported, which supports the technical stability of the application. Some participants emphasized the realism of the simulation and its relevance for skill development, particularly in the early stages of firearms training.

These observations reinforce key strengths of BellatorVR, including visual fidelity and precision in interaction. However, user feedback also pointed to potential areas for enhancement, such as expanding the weapon selection, improving interaction physics, and integrating haptic feedback to increase immersion.

It is important to note that this was an exploratory pilot study, and the findings are not intended to support broad generalizations. Rather, they serve as preliminary evidence to guide future development and evaluation efforts.

5. Final Considerations

This study presented the development and initial evaluation of BellatorVR, a virtual reality simulator for firearms training in immersive and controlled environments. Through a pilot study with four participants, initial feedback indicated positive perceptions of realism and usability, particularly for early-stage instruction. Although the sample size limits generalization, the results suggest that BellatorVR has potential as a complementary training tool.

One of the main anticipated challenges is adapting different weapon models to support realistic interaction, due to variations in grip and trigger design. The current system is configured for a single firearm, and expanding the weapon library will require specific adjustments. Future work will also focus on refining physics and enabling scenario customization to support broader training contexts.

BellatorVR was developed for the standalone Meta Quest 3 headset, which eliminates the need for external sensors or high-performance computers. This hardware independence significantly reduces deployment costs, making the system a feasible option for institutions with limited budgets that seek accessible and scalable training solutions.

In the long term, BellatorVR may also serve broader audiences beyond the military domain, including security companies, shooting clubs, and other organizations requiring safe and repeatable firearms training. Continued development and validation with larger participant groups will be essential to confirm its effectiveness and expand its applicability across different training scenarios.

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