Virtual Reality for Detailed Visualization and Generation of Proximal and Distal Bone Fracture Patterns

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Abstract: This paper articulates the application of virtual reality (VR) in facilitating the study of bone fractures, particularly those affecting the proximal and distal end segments of long bones, areas of the bone in which there are a large number of irregularities. With the increasing prevalence of bone fractures due to aging and increased life expectancy, we present an innovative virtual reality system that meticulously generates and visualizes bone fracture patterns in three dimensions. The system allows users, including healthcare professionals, to interact with 3D bone models and delineate fracture patterns in a realistic environment. It features haptic feedback, simulating the sensation of drawing on a real bone. The tool also provides an exporting functionality for the drawn fractures, enabling the integration into other medical platforms. Experts have evaluated the interaction and representation of the fracture patterns in a highly positive evaluation. The experts assessed the system positively, emphasizing its potential towards enhancing surgical planning, improving patient outcomes, and fostering educational advancements. Future work aims at improving the degree of realism within the VR environment and refining the precision of closing fracture lines.

1 INTRODUCTION

The increase in life expectancy has led to a higher incidence of fractures, mainly due to the gradual wear and tear associated with daily activities. This natural aging process often weakens bones, making them more susceptible to fractures. A complicating factor in the treatment of fractures is the interference of blood at the site of the injury, which can obscure the surgeon's view and make it difficult to align the bone fragments. As a result, secondary surgeries are often required to properly realign these fragments.

The elderly are particularly at risk for hip fractures, an injury that poses significant health risks and can lead to serious consequences such as reduced mobility and increased dependency. These fractures are particularly challenging due to the complex nature of the hip joint and the essential role it plays in weight bearing and movement. Therefore, in this work we will focus on the use of long bones, with particular emphasis on the use of the femur, as it is one of the most common fractures and has the greatest impact on people.

The study of bone fractures helps to understand the nature and morphology of these injuries, which is crucial for the development of effective and personalized therapeutic strategies. In this context, virtual reality is emerging as an innovative tool that is revolutionizing the study of bone fractures. The application of virtual reality in the medical field allows health care professionals to visualize the complex anatomy of bone fractures in three dimensions. This facilitates a deeper analysis of the unique characteristics of each fracture, such as the orientation of the fracture lines, the dispersion of the bone fragments, and the structural integrity of the affected bone, as well as improving the precision of surgical planning and patient outcomes.

The proximal and distal segments of bones typically exhibit numerous irregularities, making it quite complex to draw a fracture pattern in these areas. The common approach involves creating a 2D design and mapping or projecting it onto the bone model (Parra-Cabrera et al., 2022). However, the traditional method cannot be effectively applied in these bone regions,

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often necessitating the use of 3D drawing devices, such as haptic devices. This work presents a virtual environment for drawing a wide range of fracture patterns, including the most deformed areas of human bones, for export and use in other medical tools. The VR allows us to generate a three dimensional interactive environment for detailed visualization of fractures, including the orientation of fracture lines and deformities on the bone surface. It is particularly useful for examining complex areas of bone fractures, such as the proximal and distal end segments. The tool also allows healthcare professionals to export these fracture patterns for use in other medical tools. It enables healthcare professionals to meticulously examine the anatomical intricacies and complexities of fractures within challenging anatomical regions, such as the proximal and distal ends of bones. This precise, 3D visualization fosters comprehension of the specific fracture geometry, empowering surgeons to devise tailored surgical strategies. Moreover, it furnishes aspiring surgeons with an interactive tool for honing practical skills, enabling them to practice fracture identification and treatment within virtual environments prior to real clinical scenarios.

The outline of this work is as follows: In the next section, we analyze the previous work on medical applications in virtual reality. After the background, the materials used and the system developed are described in detail. The following sections present and discuss the results obtained in the process of using the simulator. Finally, the conclusions summarize the main advances and lines of work for the future.

2 RELATED WORK

Progress in bone fractures is essential for the diagnosis and recovery of the patients. These studies contribute to improving practices and technologies for treating fractures, including fixation methods, plates, screws, and prostheses. The study of bone fractures from a forensic and anthropological perspective reveals crucial information to determine the cause of death or the lifestyle of the subject, as each bone and fracture is unique and the anatomy of the fracture varies according to various biological factors such as age, bone density and diseases that affect bone strength (Jones, 2010; Azar et al., 2020). Although they are different, there are certain patterns in their shape when they are produced under similar conditions (Pérez-Cano et al., 2023). AO Trauma International and Orthopaedic Trauma Association Representatives (AO/OTA) presented a compendium for the classification of bone fractures and dislocations (Meinberg et al., 2018). The number of pieces of bone detached, the angle and the shape of the fracture lines are the elements that allow differentiating the different types of bone fractures. However, the shape of the bone is not uniform and the areas with the most irregularities are those where it is most difficult to extract a fracture pattern for replication in another clinical case. In the case of long bones, the irregularities are usually found at the ends of the bone, that is, the proximal and the distal end segments of the bone (Fig. 1).

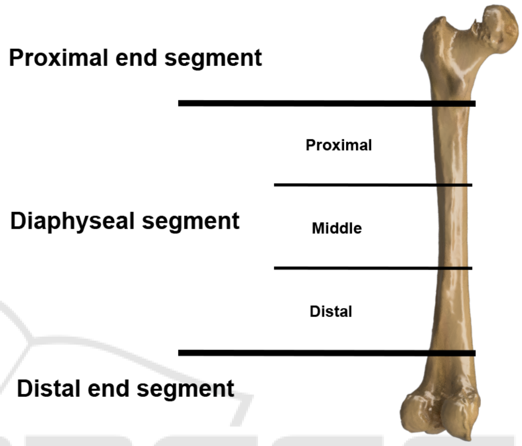

Figure 1: The areas of a long bone in which a fracture is likely to occur.

Several authors emphasize the importance of using new technologies to achieve realistic visualization when conducting a medical simulation (Tsai et al., 2001; Citak et al., 2008; Vaughan et al., 2016; Gusai et al., 2017; Negrillo-Cárdenas et al., 2021; Fu et al., 2022; Loetscher et al., 2023). Citak et al. (Citak et al., 2008) concluded that the use of technology to improve visualization and interaction allowed them to improve the planning of a bone fracture reduction by obtaining a more accurate result in the surgical process. Tsai (Tsai et al., 2001) also concludes that simulations in a virtual environment allow better planning, mainly by improving the visualization of the fracture area. Florence Aïm et al. (Aïm et al., 2016) have demonstrated the effectiveness and advantages of using VR to train new surgeons. However, most virtual reality based studies have focused on fracture reduction planning and training.

Some authors report that the use of VR also helps participants to feel motivated and interested in participating in this type of projects (Herne et al., 2022; Reer et al., 2022). Among other aspects, immersion, interaction and feedback are highlighted as fundamental elements. Herne et al. (Herne et al., 2022) emphasize the importance of feedback in providing a good experience to the user who tries the tool. Gusay et al. (Gusai et al., 2017) focused on analyzing the interaction of a user in a realistic environment. In this work, they analyze the different ways a user can interact with the environment using different devices compatible with the HTC Vive head-mounted display (HMD) to visualize the scene.

Negrillo et al. (Negrillo-Cárdenas et al., 2021) developed a fracture reduction system based on VR using contralateral fractures as targets. They observed a high learning rate when using the system and a reduction in simulation time as more trials were performed. Vaughan et al. (Vaughan et al., 2016) reviewed the main existing fracture reduction simulation environments, as well as the problems with some of them. In this study, the authors also conclude that there is strong evidence that the skill level of trainees in medical procedures can be assessed using VR simulators. Akhtar et al. (Akhtar et al., 2015) demonstrate the validity of a haptic VR trauma simulator, with surgeons performing the procedure most often performing best on the simulator. Homma et al. (Homma et al., 2019) also worked along these lines and came to the same conclusion.

Loetscher et al. (Loetscher et al., 2023) conducted a recent study in which they concluded that there is evidence that the integration of virtual reality in the medical field is extremely beneficial and that it should be used more often to take full advantage of its benefits. Some companies, such as Meta, are moving in this direction to provide ecosystems to support the growth of virtual reality in the medical field. However, it is a process that will take some time before it becomes a necessity for healthcare.

3 MATERIAL AND METHOD

The project was developed using the Unity engine, a leading game engine known for its ability to support interactive 3D content and broad cross-platform compatibility. The virtual reality experience was delivered through the HTC Vive Pro Kit, chosen for its high-resolution display and advanced tracking capabilities. By using the advanced Lighthouse tracking system, also known as base stations, we obtain a millimetric accuracy for user positioning. This level of accuracy makes this VR system ideal for simulating the intricacies of an operating room environment. The immersive experience is further enhanced by the wide range of hardware sensors, including proximity sensors, gyroscopes, and infrared sensors. In addition, the controllers are designed to provide seamless interaction with the virtual environment. They incorporate tactile feedback through vibration, allowing precise manipulation of three-dimensional objects, such as human bones in our simulation. The user can interact with the environment using two controllers held in the right and left hands. The equipment used to support the virtual reality application consists of a computer equipped with an i7 microprocessor, 8GB of RAM, and an NVidia 1060 graphics card.

The virtual environment design consists of an operating room (Fig. 2). A familiar space has been recreated for the surgeons to increase the level of immersion. The primary function of our tool is to allow the user to delineate and examine fracture patterns on highly detailed 3D models of long bones, focusing on the complex and irregular areas such as the proximal and distal end segments. The user can select between different long bone models to draw a fracture using the controllers.

Figure 2: Environment used to conduct the simulation.

The left controller allows the user to move around the environment and move the model to improve the viewing angle, while the right controller allows the user to create the fracture pattern. To create a fracture pattern, the controllers emit a laser beam in the direction they are pointed. When this laser intersects the bone model, it creates a visible line on the bone surface that represents the fracture line. The points forming the fracture line are calculated by the intersection between the mesh and the beam leaving the controller, using the algorithm of Möller and Trumbore (Möller and Trumbore, 1997). The user must hold down the trigger to add points to the polyline that defines the fracture line (Fig. 4). In addition, the fracture line must be fully closed and connected for the fracture to be valid and exported. It is not necessary to draw the line in one go, the user can add points to the fracture line one at a time and confirm when the fracture representation is complete. This mechanism facilitates the elimination of incorrect points marked by the user, since a history of the various iterations with the model and the points selected is stored, so that errors can be corrected as the fracture line is drawn. Figure 3 shows the graphical interface that can be used by the user within the virtual environment when drawing the fracture pattern on a human bone. Moreover, the user defines the end of the representation of the model and it is automatically validated by a study of the continuity of the polyline. If the polyline is not closed, the user is prompted to continue with the design of the pattern.

Haptic feedback is integrated to enhance the tactile experience, giving the user the sensation of drawing on a real bone through small vibrations. This feature is particularly useful for medical professionals, as it adds a layer of realism that is critical to understanding the physical characteristics of bone fractures. The intensity of the vibration is slightly increased when the user is drawing the fracture line and it is in a hole or a bump is found in the geometry of the model. The vibrations are managed by assessing the distance variations between the position of the controller and the specific point on the bone model where the laser beam intersects during the drawing activity. When the user move the laser over the bone's surface, the occurrence and intensity of vibrations depend on the difference in distance between consecutive points along the fracture line.

An essential feature of this tool is the ability to export the drawn fracture lines. This functionality allows the fracture patterns to be integrated into other tools. For this purpose, we have exported the point cloud drawn by the user. We are currently working on the import of the fracture lines generated in this tool, so that it will not only serve to generate fracture patterns, but also to improve the visualization or the lines of existing patterns obtained with this or other medical tools.

4 RESULTS

The previous section has detailed the development of a virtual reality application to delineate and examine fracture patterns on highly detailed 3D models of long bones, specifically focusing on the complex and irregular areas of the bone surface. In this section we show the result obtained and we focus on the evaluation of the results obtained and how to analyze them to validate the quality of the system designed. For this purpose, we have conducted extensive tests to validate the application.

There is no other system with a similar purpose. Therefore, the design and functionality have been refined in collaboration with three specialists with experience in bone fracture reduction, a physiotherapist and an orthopedic surgeon. Each of the 5 users was tasked to replicating a fracture type from the AO/OTA classification in the proximal and and distal area of three different bones: a femur, a humerus and a fibula. The fibula can be considered the simplest model, given that the deformity at the ends is smaller. It has been presented as the initial case to test the developed tool. The humerus and femur exhibit more significant deformities, with the femur being the most irregularly shaped and representing the most complex case presented to the specialists. Each bone has a different shape in these sections. Before starting the tests, they were instructed on the controls necessary to select the bone, rotate it and how to draw the fracture line on it using the HTC Vive controllers. Technical testing focused on system performance, stability, immersion and user interface usability.

Figure 5 shows different fracture patterns drawn by experts on the end segment of the epiphysis of a human humerus. All the patterns are based on the AO/OTA classification (Meinberg et al., 2018). The image shows all the fracture lines that make up the pattern in red. In addition, the lines drawn on the back of the model, the non-visible part of the geometry, are shown so that the user can take them into account when closing the lines completely. Figure 5a represents an oblique fracture in the surgical neck area. Figure 5b shows a wedge-shaped fracture without fragmentation at the head of the humerus while figure 5c shows a compound fracture with many fragments in the same area. The visual improvement is considerable when defining the patterns, since the simulator allows the deformations of the bone surface to be identified with a high level of detail. Figure 6b shows the view of the fracture pattern from the longitudinal axis of the bone on which it is drawn (Fig 6a.).

A survey was used to evaluate the tool using a 5-item Likert scale. Table 1 shows the median and average results obtained through the survey in the different aspects considered. In general, most aspects were rated positively by the expert group. Among the main evaluations, the scores for the interface and the drawing of fracture lines on the bone model stand out, where all experts agreed with the maximum score. This reflects the fact that the developed tool has an intuitive interface and sufficient functionality to draw the patterns in the most complex areas in a simple way.

We can see how the complexity increases when it comes to completely closing the fracture lines in the questions about painting the fracture lines. The high precision of the controls makes it a complex task to completely close the fracture line, as the start and end points did not coincide. Achieving this task demands

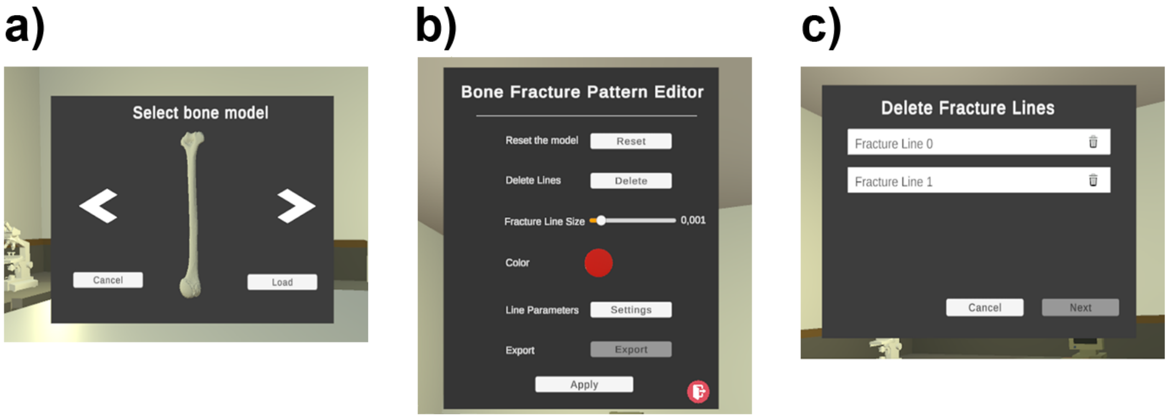

Figure 3: Editor interface for drawing fracture patterns. a) Bone selection menu, b) Drawing configuration menu, and c) Fracture line deletion submenu.

Figure 4: Interaction system to draw the fracture bone pattern using the controllers.

Table 1: Results of the user experience survey in the VR environment.

Item	Median	Average
Interaction	5	4,6±0,49
Interface	5	5
Draw fracture lines	5	5
Join fracture lines	4	4±0,40
Close fracture lines	4	3,8±0,40
Delete fracture lines	5	4,6±0,49
Learning curve	3	3,4±0,49
Immersion and realism	3	3,2±0,40
Fluency	5	5

significant user dexterity. In the future, an automated system will be incorporated to assist users in closing the fracture line.

The degree of realism and immersion of the tool and the learning curve stand out as the worst aspects evaluated by the experts. The experts informed us that the enhancement in bone visualization is significant, but they noted that the environment surrounding the bone fell short of resembling a real operating room. This is due to the fact that the tool was designed to improve the visualization of fracture lines and deformities on bone surfaces, somewhat omitting the environment in which the simulation was developed. Therefore, this is an aspect that needs improvement in the future. On the other hand, although the interaction mechanisms were rated as intuitive, reproducing a clinical case without training the user is not trivial. The initial training proved insufficient to facilitate rapid and accurate pattern drawing. However, as participants advanced through the tests, the rendering of fracture patterns became quicker and more precise, resulting in a reduction of poorly drawn lines during the process. In future versions, an initial scene will be included to train users in the use of the tool and to facilitate the drawing process.

Subsequently, the experts were asked to perform the same tests with a keyboard and mouse without a virtual reality environment. Table 2 presents feedback obtained by the experts after assessing the system without the virtual environment. While they noted that the new system was more comfortable, the interaction to draw the fracture patterns and the visualization was noticeably inferior. Achieving a specific perspective for model visualization proved to be a rather tedious task with the mouse. Moreover, the accuracy in drawing lines was not as precise as in the VR environment. As depicted, the scores decrease in almost all aspects evaluated. However, the learning curve is lower than in the virtual reality-based system. This may be attributed to users being more accustomed to use this type of device for interaction with a 3D environment.

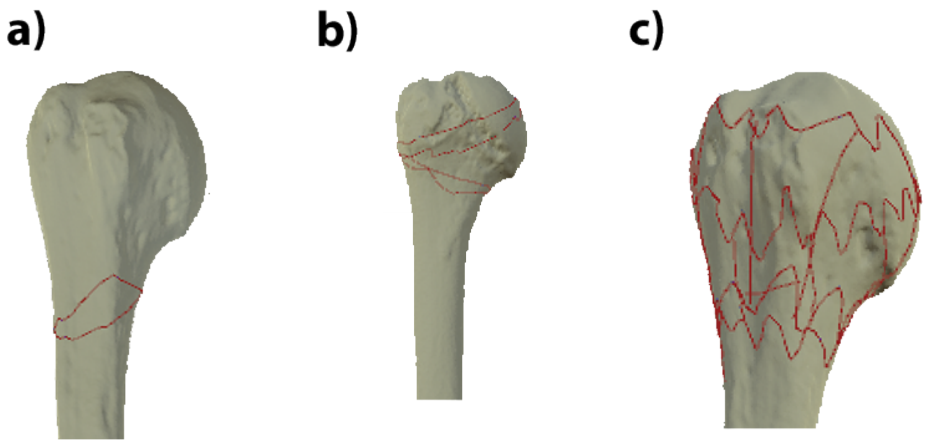

Figure 5: Different fracture patterns drawn in the end segment of the epiphysis of a human humerus. a) Represents an oblique fracture, b) a intact wedge fracture and c) a fragmentary fracture.

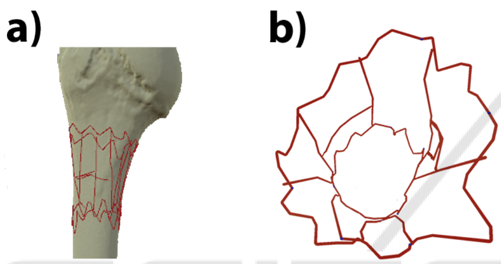

Figure 6: a) Fracture pattern on a bone model. b) Fracture pattern observed from the longitudinal axis of the bone model.

Table 2: Results of the user experience survey without the VR environment.

Item	Median	Average
Interaction	5	4,6±0,49
Interface	5	5
Draw fracture lines	3	3,4±0,49
Join fracture lines	3	3±0,63
Close fracture lines	3	2,6±0,8
Delete fracture lines	5	4,8±0,4
Learning curve	4	4,4±0,49
Immersion and realism	3	3 ±0
Fluency	5	5

5 DISCUSSION

VR allows users to interact with 3D models of fractures in an immersive environment, providing a more realistic and robust understanding of fracture characteristics compared to traditional 2D imaging methods. This includes understanding complex structures, orientations of fracture lines, bone deformities, and details about bone fragment dispersion.

As the VR environment allows users to modify viewing angles freely, this assists in creating precise surgical plans as one can explore the fracture from various perspectives that might not be possible with traditional imaging. The capability to draw fracture lines directly on the 3D bone models within the VR environment also enhances the precision and personalization of surgical planning.

Haptic feedback is integrated into the VR tool, providing the sensation of drawing on a real bone surface via vibrations, improving the tactile realism. This can be particularly useful for tactile learners and enhances the overall understanding of the physical characteristics of the bone and fractures. Furthermore, since the VR tool allows exporting of fracture patterns, these can be integrated with other medical tools or simulations, which can boost surgical planning or training processes.

The primary advantage, however, is that VR gives the potential to rehearse, repeat, and correct procedures virtually before performing actual surgery, which can improve the likelihood of positive patient outcomes.

6 CONCLUSIONS AND FUTURE WORK

This research has successfully demonstrated the application of VR in the medical field, particularly in the study of bone fractures. We have created a system that allows medical professionals to visualize and interact with 3D models of long bones to draw fracture patterns. This technology has proven to be particularly effective in examining the complex areas of bone fractures, such as the proximal and distal end segments.

The application developed significantly improves the visualization of bone deformities as well as the interaction to represent different clinical cases of fracture on human bones. In addition, haptic feedback is included when drawing, using the changes in the geometry of the model. The ability to draw and manipulate fracture lines directly on the bone models has been highly rated by experts, reflecting the relevance in medical practice. Moreover, the ability to export these fracture patterns enhances its application in various medical scenarios, extending its utility beyond mere visualization. These patterns can be used in other medical tools, facilitating a more comprehensive use in diagnostics, treatment planning, and educational purposes.

The extension of the variety of patterns generated with the tool enables a wider range of fractures to be covered. This is a key element as the extension makes it possible to work with a wider range of medical scenarios or generate databases with more accurate information about the fracture area.

However, certain challenges such as the precision in closing fracture lines and the degree of realism and immersion need to be addressed. While the tool excels in visualizing fracture lines and bone deformities, improvements in the simulation environment and user training are required for a more comprehensive application.

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