Virtual Reality Environment for the Validation of Bone Fracture Reduction Processes

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Abstract: This work presents a virtual environment for the validation by experts of computer-assisted bone fracture reduction. This environment is composed of VR glasses and 3D controllers (HTC Vive) that allow interaction and immersion in the scene in a realistic way. The virtual environment developed allows loading fractured bone models (fragments) so that the specialist performs a virtual fracture reduction and its results can be used for the validation of algorithms and assisted reduction techniques. Once the fragments are loaded, the user can perform an interactive reduction of the fracture, visualizing the fragments in 3d from different views, moving the fragments in 3d and placing the fragments in space to observe the reduction in detail. Once completed, it allows the reduction to be exported so that it can be compared with other fracture reduction systems. The system has been tested by specialists in traumatology and a usability study has been carried out. Finally, the system has been empirically validated and used to compare the performance of other computer-assisted reduction systems.

1 INTRODUCTION

Fracture reduction is a surgical procedure to repair a fracture or dislocation in the correct alignment. This sense of the term reduction does not imply any type of elimination or quantitative decrease, but rather implies a restoration. It must be taken under consideration that multiple fragments can be generated in a fracture, some of them with microscopic size. The reduction of a fracture requires the union of the larger fragments, ignoring the smaller ones. Therefore, the reduction of a fracture does not imply that the fragments must be completely joined at all points.

When a bone is fractured, the fragments lose their alignment in the form of displacement or angulation. For the fractured bone to heal without any deformity, the bone fragments must be realigned to their normal anatomical position. Orthopedic surgery attempts to recreate the normal anatomy of the fractured bone by reducing displacement.

The goal of virtual reality is to create an immersive environment that is as realistic as possible. The use of virtual reality to work with bone fragments, improves the visualization, the perception of the fracture zone, to achieve a better reduction, and the interaction of the user with the fragments is more realistic. These features allow the use of the tool to perform precise fracture reductions and their subsequent comparison with reduced fractures using fracture reduction algorithms allowing validation of the results. In addition, it could be extended as a training tool for fracture reduction, although the focus of the tool should be the inverse, with the help of experts, datasets of fractures can be manually reduced to provide a reference to validate the results of algorithm.

The summary of this article is as follows. In the next section we analyze the previous work on reduction of bone fractures, analyzing the methods used for the validation of the obtained models. It is complemented with information on other fracture reduction simulation environments. After the background the design of the tool for the validation of fracture reduction processes is presented. The following section presents and discusses the results obtained in the process of using the simulator for validation. Finally, the conclusions summarize the objectives of this tool and propose the work to be developed in the future.

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2 BACKGROUND

At the moment, data banks of bone fractures and healthy bones are still inaccessible and a challenge for the future. Pérez and Jiménez (Pérez-Cano and Jiménez-Delgado, 2019a) have developed a tool that allows the fracturing of bones and the obtaining of the different fragments, figure 1. The problem with this approach is that it is necessary the use of bone models and the results are based on the use of 2D fracture patterns so that information about the fracture is lost and is not entirely realistic. Therefore, the easiest, and most accurate method of obtaining 3D bone models, is the segmentation of medical images of real fracture cases. There are other approaches to obtain geometric models of bones such as 3D scanning that yield similar results, but the main problem they have is time and loss of accuracy as identified by Pérez and Jiménez (Pérez-Cano and Jiménez-Delgado, 2019b) in evaluating the different approaches to obtaining a geometric bone model. Paulano (Paulano et al., 2014) concluded that traditional segmentation methods work correctly with healthy bones, but that in fragmented bones, it was not possible to identify the different fragments that make up a fracture. Paulano also proposes a method based on 2D region growing (Justice et al., 1997; Fan et al., 2005). This method is based on the establishment of several seeds along the bone so that the regions grow and allow the identification of the different fragments.

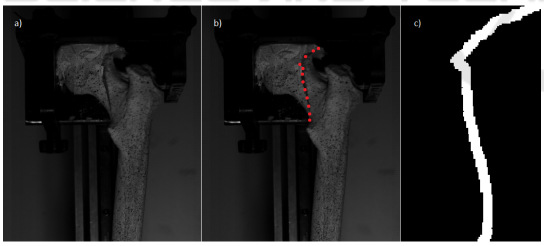

Figure 1: Extraction of the fracture pattern through the fracture of a femur after a process of mechanical experimentation. Figure a represents the femur at the time the fracture occurs, figure b indicates the fracture zone with red colour and figure c the fracture pattern obtained. Extracted from (Pérez-Cano and Jiménez-Delgado, 2019a).

Studies such as the directed by Citak (Citak et al., 2008), emphasizes the importance of using new technologies to achieve a more realistic visualization. As demonstrated in this study, improved visualization and interaction allows for better planning of fracture reduction and therefore obtaining more precise and efficient reductions as a result. The advantages of virtual reality in the field of bone fracturing have been known for quite some time. Tsai (Tsai et al., 2001) also conclude that simulations in a virtual environment allow better planning, mainly by improving the visualization of the fracture, and obtaining better results. In terms of interaction in these environments, Gusai (Gusai et al., 2017) analyzed the interaction of a natural user in a realistic environment. The controls of virtual reality systems have 6 degrees of freedom, as in the case of HTC Vive. The use of these devices are more intuitive in positioning tasks in immersive environments compared to the use of other types of options such as the use of gestural interfaces.

There are currently many works that attempt to increase the degree of automation of bone fracture reduction, but there is no standardized way to validate the results obtained. The most direct and evident method is a subjective visual assessment, but this does not provide quantifiable results although it serves to validate results from quantitative methods. One of the forms used to objectively validate the reduction of bone fractures is the comparison with the symmetrical bone (Fürnstahl et al., 2012; Vlachopoulos et al., 2018) of the same patient. This is not always possible since in real clinical cases only the study of the fracture area is normally done, mainly because of the cost in money and time. There are occasions in which it is not possible to obtain the scan of the symmetrical bone, bones that do not present symmetry, medical anomalies or traumatisms with fracture in both bones. When studies are performed on donated human bones or on animal bones, which are mechanically fragmented to simulate different types of lesions, there is the alternative of scanning the bone before and after the experiment, which permits comparison of the reduced fragments with the intact model (Liu et al., 2019). In the research by Paulano (Paulano-Godino and Jiménez-Delgado, 2017) a set of tools developed by the same team (Paulano et al., 2012) is used for the manual reduction carried out by experts, then the measurements are extracted and compared with the reduction obtained by its algorithm to extract the difference in translation and rotation between manual and automatic reduction.

Lately a multitude of Virtual Reality, Augmented or Mixed devices have appeared, which have been tested in hospital environments and facilitate the reduction of a fracture. This work aims to address the problem of validating the reduction of bone fractures based on the work of Paulano (Paulano-Godino and Jiménez-Delgado, 2017), taking advantage of advances in computer person interaction and visualization using Virtual Reality techniques.

3 VIRTUAL ENVIRONMENT

The proposed virtual reality environment has been implemented using the Unity graphics engine, as seen in figure 2. This tool recreate a virtual world familiar to future users of the system, an operating room, with the aim of improving immersion and focusing users in a surgical environment for fracture reduction. The hardware incorporated in the HTC Vive bundle provides full immersion, the kit is formed by a VR helmet with multiple sensors to determine its spatial position, proximity sensors and gyroscope. For the control of the environment, it incorporates controllers that allow manipulating the fragments in 3D space and provide feedback through vibration.

The system allows to select a fragment, place it in the space and proceed to perform the reduction with the remaining fragment, figure 3. The first time that a fragment is selected, by clicking the right trigger while the beam touch it, it jumps in front of the right controller and stays connected to to motion of the controller, once the user click the right trigger again the fragment changes to a non selected status and starts to follow the left controller. Non selected fragments stay attached to the left controller, so the user can move and rotate independently the inactive fragments with the left hand and the selected fragment with the right hand, this allows users to observe the reduction process from different angles to improve results. The fragments on the left hand can be selected as many times as necessary, the second and subsequent times when the fragments are selected they do not move to the right controller, they only get attached to it so the user can make small corrections.

Throughout the process the user receives continuous feedback through vibration and visualization of specific elements located on the fracture zone when the fragments collide, to perceive the interaction between fragments like a real collision. These components are called ”colliders” in the Unity system, in figure 4 shows the active colliders as small yellow spheres.

Once a satisfactory result is reached the reduction can be finished by clicking the left trigger, figure 5 presents a reduced fracture with Windows Mixed Reality controllers, the use of Unity allows the application to be multiplatform and compatible with a wide range of RV helmets. Finally, the relative positions of both fragments, translation and rotation, are stored and used as ground truth to compare the results from other automatic or semi-automatic fracture reduction systems.

4 RESULTS AND DISCUSSION

As has been seen in previous sections, virtual reality provides better visualization and greater control over daily actions. In the field of traumatology, an immersive environment allows the users to have better conditions when conducting studies. In this section, the advantages of the tool for reducing bone fractures are analysed, comparing the results achieved with the obtained through studies of a similar scope. A research has also been carried out about the experience of the use of the tool by experts in fracture reduction processes.

4.1 Automatic versus Manual Reduction

A software has been developed that allows the validation of automatic algorithms for the reduction of bone fractures using the bone reductions conducted by experts in a virtual environment as the ground truth. Thus, the error is then calculated as the absolute value of the difference between the result of the automatic and manual reduction in translation and rotation, the closer each value is to zero, the more accurate it is.

The first parameter is the distance error between the two fragments measured from the center of mass of each model. The second one is the rotation error that was calculated in two ways, as the average difference around the fragments three 2nd moment vectors, proposed by Paulano (Paulano-Godino and Jiménez-Delgado, 2017), and as α and β errors, used in the work of Fürnstahl (Fürnstahl et al., 2012). α is the difference around the two largest 2nd moment vectors and β represents the rotational difference around the smallest 2nd moment vectors.

In experiments, some cases has been tested and compared with the results obtained by the algorithm of Paulano (Paulano-Godino and Jiménez-Delgado, 2017). In complex cases, when the fracture consist of more than two fragments the reduction of the fracture is applied in pairs, that means, first two fragments are reduced, one to each other, and then the obtained fragment is reduced with the remaining fragment. Figure 6 illustrates the automatic reduction of the fibula fracture, the same fracture used in section 3 to demonstrate the functioning of the virtual environment. The fracture of the tibia is composed by three fragments, the second reduction was performed using the previous reduction of fragment 1 and 3 and fragment 2.

At final stages of development, the system was used to tune the parameters of a automatic fracture reduction process based on a modification of the ICP algorithm, which is being currently devel-

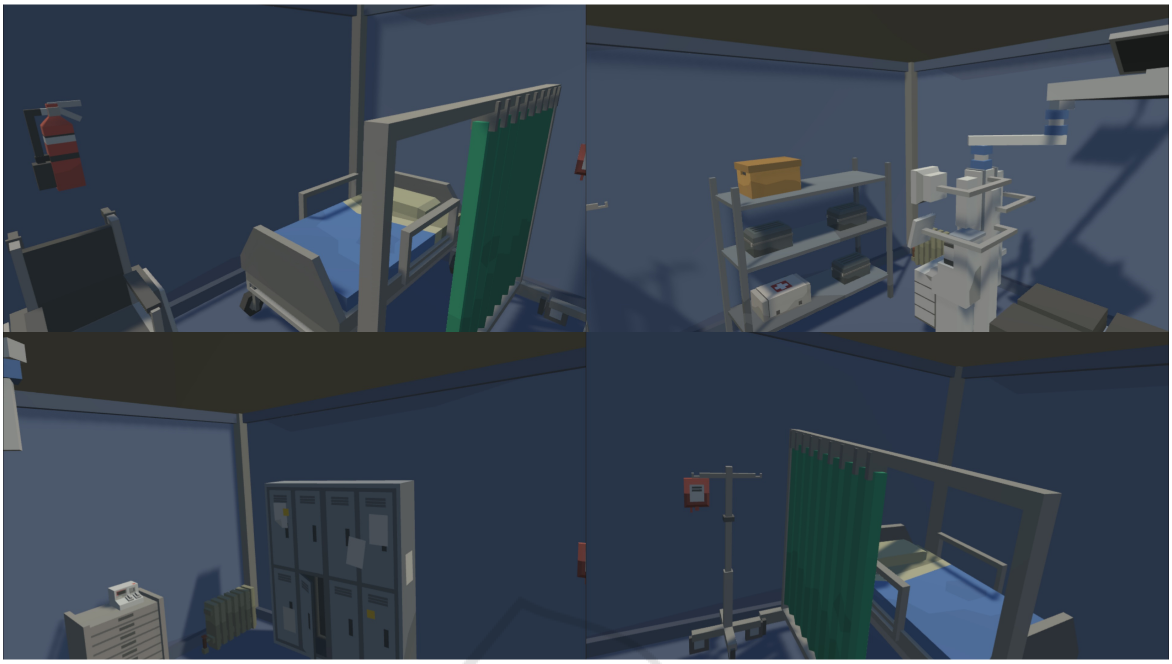

Figure 2: Scene designed in Unity of the virtual environment.

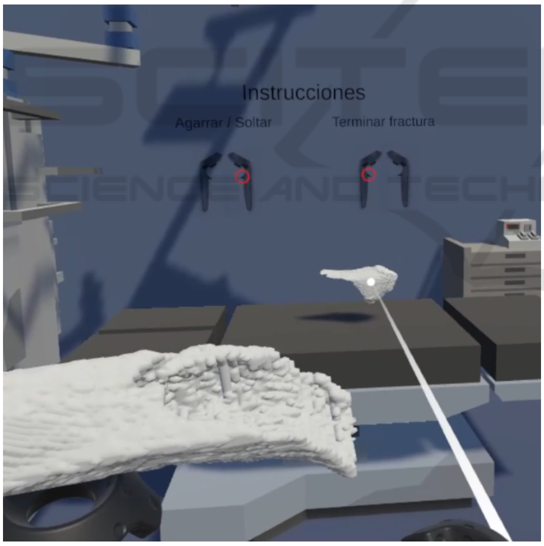

Figure 3: Bone fragment selection system, the beam emitted from the controller improves accurate picking.

oped. The table 1 shows the results of the new algorithm, which are very promising, improving those obtained in the works of Paulano (Paulano-Godino and Jiménez-Delgado, 2017) and Fürnstahl (Fürnstahl et al., 2012), table 2.The average translational error has been reduced from 1.80 and 1.11, Paulano and Fürnstahl results respectively, to 0.58, which represents an average increase in accuracy of 100%. The rotation error in the work of Paulano is 3.25, Fürnstahl

Figure 4: The colliders are shown as small yellow spheres that generate haptic feedback in the controllers.

obtains an error value in alpha and beta of 3.1 and 3.51, the algorithm in development has achieved values of 2.41, 3.30 and 0.92 in such parameters, only the alpha error is slightly worse but the beta value has been really improved.

The error of the fracture reduction algorithm could be minimized thanks to this framework, once reached a certain level of precision in the reduction of fractures is difficult to differentiate visually if one result is better than another. This is why it is important to create an environment and a standardized process in which the results in fractures of any bone can be compared and improved.

One of the most important advantages of virtual reality is the simplicity of use, replacing the interaction with keyboard and mouse by a more immersive

Table 1: Results of an improved experimental reduction algorithm achieved with the aid of the developed system.

Fracture	Fragments	Translation error (mm)	Rotation error (mm)		
			Average	Alpha	Beta
Humerus	1 → 2	1,3202	1,3902	1,8582	0,6494
Fibula	1 → 2	0,2945	3,2845	4,5854	1,1135
Tibia	1 → 3	0,3586	3,9431	5,3503	1,6489
Tibia	1 3 → 2	0,3283	1,0213	1,4163	0,2622

Figure 5: Successful reduction of a fibula fracture with a Windows Mixed Reality device.

Figure 6: Improved automatic reduction of a fibula fracture thanks to the use of the developed framework.

experience with elements that track in real time the head and hands of the user, which achieves a completely natural interface to the 3D world. For this reason, the learning time is practically non existent compared to the use of a 2D environment. This software has been tested by three different user profiles, all users have been able to successfully reduce several bone fractures without the need to spend a great deal of time reducing a bone fracture.

The equipment needed to run the virtual reality framework is noticeably more powerful, we have used

Table 2: Average results of different algorithms when evaluating errors.

Study	Traslation	Rotation	Alpha	Beta
Furnstahl	1,11	—	3,10	3,51
Paulano	1,80	3,25	—	—
Original	0,58	2,41	3,30	0,92

a PC equipped with a first generation i7 microprocessor with 8GB of RAM, an NVidia 1060 graphics and the virtual reality glasses, HTC Vive.

4.2 Usability Tests

The system has passed through a validation process in which a sample of specialists has been selected. This user group formed by two experts with experience in fracture reduction, two users with experience in the use of fracture reduction applications and a radiologist expert in the analysis of traumatology images. In addition to the difficulty of finding real cases of bone fractures due to confidentiality reasons, the collaboration with the medical community has proved more costly than expected, mainly due to the lack of time of the professionals and the rejection that such recent technologies produce.

Table 3: Results of the user experience survey.

Feature	Rating
Image quality	4.83±0.37
Immersive sensation	4.83±0.37
Realism	3.83±0.69
Graphics fluidity	4.50±0.50
Intuitive control	3.66±0.94
Learning curve	4.33±0.47

To conduct the usability study, the virtual reality device was first shown to users, equipped with it, and asked to observe and interact with the environment without explanation of the application workflow. In order to evaluate the first impression of the system, a questionnaire had been designed with general questions about the quality of the images, immersive sensation, realism, fluidity of the graphics, intuitive control and learning curve. The questionnaire has been

Table 4: Results of the questionnaire about the reduction process.

Fracture	Ease of selection and movement of fragments	Accuracy and feedback of the collisions	Ease of the reduction process	Accuracy
Fibula	4.66±0.62	3.83±0.99	4.16±0.69	4.16±0.69
Femur 1	4.75±0.43	3.83±0.80	3.66±0.75	4.00±0.58
Femur 2	4.66±0.47	3.75±0.43	3.33±1.11	3.50±0.76
Femur 3	4.83±0.37	3.58±0.49	3.16±0.69	3.33±0.47

Table 5: Score of the reductions granted by the experts.

Fracture	Accuracy
Fibula	4.50±0.60
Femur 1	4.66±0.82
Femur 2	4.83±0.47
Femur 3	3.83±0.80

designed using five level Likert responses.

Table 3, shows that the experience of use is really satisfactory, only two values, "realism" and "intuitive control" obtain a score slightly lower than 4 points. According to users, the low level of realism is mainly due to the resolution of the models, which have been extracted from CT images without applying any smoothing filter that could reduce accuracy, and to the scale applied to easily handle the smaller fragments. The score in this aspect could be improved in the future by applying an algorithm to smooth the model obtained after segmentation, but preserve as much detail as possible.

The lowest value was "intuitive control", which is to be expected considering that the use of the software has not been previously indicated. Subsequently, brief instructions for the reduction procedure have been provided to each user, after which they have been asked to perform four reductions of bone fractures with two fragments each.

After completing the reductions, they were asked to answer a questionnaire about the ease of selection and movement of the fragments, the accuracy and feedback of the collisions, the ease of the reduction process, and finally each user was asked to rate the accuracy of the result obtained (table 4). The values obtained in relation to ease of movement and selection validate the user interface implemented using the VR controllers, while the score associated with feedback indicates a need to adjust the vibration response curve.

The ease of reduction and accuracy are markers that are very interrelated, if users have a perception that they do not get an optimal result they will negatively evaluate both parameters. Considering the conclusions obtained in section 4.3, it could be assumed that both aspects of the process have been subjectively evaluated by the sensation of low performance of the users.

4.3 Validation by Experts

In section 4.2, users have been asked about the experience using the system. As a result, it has been obtained low values in the perception of accuracy in the reduction. To confirm whether the value obtained is objective or users rated their own result negatively, users repeated each reduction three times and then the result of their peers was presented to each expert to be scored, to increase reliability the whole process was conducted hiding the author of each reduction.

In table 5, it can be observed that the evaluation of the reduction of fractures by the rest of the experts is greater. The fragments of the fracture femur 3 show loss of osseous material and some degree of deformation, which explains the lower level of precision appreciated.

5 CONCLUSIONS

This article proposes a system for reducing fractures using a virtual environment that provides fast and realistic results for the validation of bone fractures, as an alternative to rapid prototyping reduction of bone fragments and subsequent capture of fragment positions.

The main objective that has been sought and achieved is the validation of automatic algorithms for the reduction of fractures. For this purpose, the results generated by expert users have been compared with the results obtained from fracture reduction algorithms using different metrics defined in the results section.These results have demonstrated that the proposed process allows to compare and evaluate precisely the reductions of fractures improving those present in the literature in different aspects.

Moreover, during the creation of the system several tests have been carried out with different types of users in order to study in depth how the immersion of users in a virtual environment facilitated the reduction of fractures.These studies have proved that the improvement in visualization and interaction have been essential to the improvement of the results obtained in the reduction of fractures.

In view of the ease of use and the natural way in which bone fragments are manipulated, a future modification has been studied for use as training software for traumatologists. Although this work has been used exclusively for medical use, it could be extended to other fields such as forensic medicine or archaeology.

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