Desarrollo de un modelo numérico aplicando fundamentos biomecánicos para sanar fractura de coronoides del codo utilizando fijación con tres tornillos de titanio

Development of a numerical model applying biomechanical foundations to heal coronoid fracture of the elbow using fixation with three titanium screws

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Resumen

La fractura de codo es una de las principales limitaciones que proporciona la estabilidad de la articulación humeral. Este tipo de fractura puede ser un hallazgo aislado después de la luxación del codo o en parte de una terrible triada del codo. La luxación de codo es una lesión común, que representa el 10% de los traumatismos sobre dicha articulación. Normalmente suelen producirse por accidentes deportivos o automovilísticos En este trabajo se presenta el desarrollo de un nuevo modelo numérico del antebrazo (radio y cúbito) para ser utilizado para evaluar el proceso de fijación de tornillos esponjosos de titanio. El diseño de los tornillos se realizó de acuerdo a las normas establecidas. Así como, la fijación de los tornillos se desarrolló de acuerdo al caso clínico de un joven masculino que había sufrido previamente fractura en este sistema biológico. Cabe señalar que la posición de los tornillos es idéntica al caso clínico mencionado. También se realizaron orificios al biomodelo del codo, estos sirven para la fijación de los tornillos, otorgando confiabilidad en los análisis realizados, ya que es un modelo idéntico a la vida real. Los resultados obtenidos en esta investigación son confiables y con funcionalidad para análisis futuros.

Palabras clave; Antebrazo, Simulación numérica, Fractura, Método de Elemento Finito.

Abstract

The elbow fracture is one of the main limitations that provides the stability of the humeral joint. This fracture type can be an isolated finding after elbow dislocation or part of a terrible elbow triad. Elbow dislocation is a common injury, accounting for 10% of injuries to that joint. Usually caused by sports or car accidents. The most frequent complications are stiffness and instability. This paper presents the development of a new numerical model of the forearm (radius and ulna) to evaluate the fixation process of cancellous Titanium screws. The design of the screws was performed according to the established standards. Additionally, the fixation of the screws was developed according to the clinical case of a young male who had previously suffered a fracture in this biological system. It should be note that the position of the screws is identical to the aforementioned clinical case. Holes to fix the screws were produced in the biomodel of the elbow, providing reliability in the evaluation (since it is a model identical to real life). The results obtained in this research are reliable and functional for future analyses.

Keywords; Forearm, Numerical simulation, Fracture, Finite Element Method.

1. Introduction

Throughout its history, humanity has faced a recurring and determining problem in its bone system. There have been different malformation and fracture types, which gradually have increased over the years. Historical antecedents have been found, describing how humans treated diverse malformations and fractures [1 to 5]. These findings are of utmost importance in the area of Traumatology and Orthopedics. The elbow fracture is one of the most frequent, since it represents a surgical challenge for the Orthopedist. Which must understand and widely known the complex anatomy of the study region. But over the years and with the technological advances that have been increasing, elbow fractures can be treated easily and efficiently, due to the fact that there are new trends for surgical interventions. To treat fractures, osteosynthesis materials are used, such as plates, screws, wire, needles, among others [6 and 7]. Patients who require a surgical intervention in the elbow zone usually undergo an orthopedic treatment based on titanium screws, where it has been observed, that in most of the cases there is a favorable recovery. This is due to the surgical material, which has a degree of compatibility with the human body [8 to 11]. Nowadays, elbow fractures have been a problem for the development of human beings, although one of the main risk factors is the post-surgical recovery process. Due to the positioning of internal fixation methods (screws), since most surgical interventions in patients do not have an optimal biomechanical analysis to establish the specific point of optimal fixation [12 and 13]. The main idea for the development of this research is the numerical biomechanical analysis, which will establish certain risk factors in the fixation of screws that will occur in the coronoid fracture of the elbow. To have a solution, an analytical and numerical study of the screws fixed in the bone will be carried out (applying the Finite Element Method). Previously, a reconstruction of the bone will be performed through computed tomography, which will obtain a three-dimensional model of the bone, allowing the generation of a bone-screw system.

2. Development of the elbow bone system model

The model of the elbow was develop through computerized axial tomography. A computer program called Simpleware ScanIP® was apply to carry out the construction of the elbow model (Figure 1). This program offers the implementation of 3D models using DICOM (Digital Imaging and Communication On Medicine) images. Which generates STL files offering a wide selection of computational tools to observe images or generate 3D files.

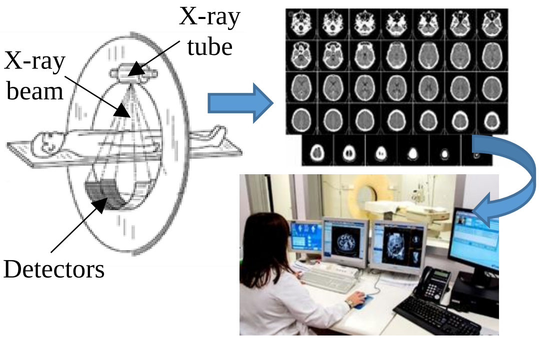


Figure 1. Schematic representation of a computerized axial tomography

Later the model will have an extension that will be generated to reliably export the model to analysis through FEM (Finite Element Method) and even prototypes of the human body could be manufactured in 3D prints [14].

The DICOM file contains the digitized images taken with the tomographer (Figure 2). It is worth mentioning that it is important to reconstruct the model utilizing the file that contains the mayor number of possible cuts. This will serve for a better refinement in the implementation of the model. With this procedure it is possible to avoid excessive surface roughness and have a model almost identical to the patient's elbow [14].

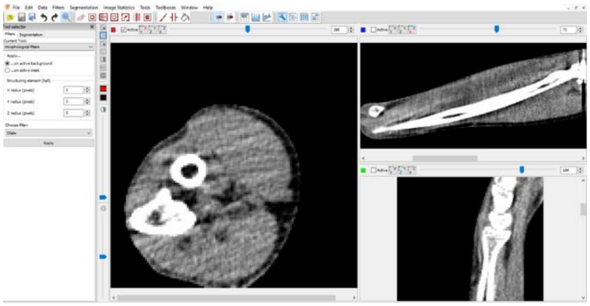


Figure 2. Import DICOM files to the Scan IP® computer program

The work area for the construction of the model is delimited (can be done in two ways; manual and automatic). This elbow model was develop by the generation of five masks (humerus bone, ulna bone, radius bone, medullary bone, and cartilage (Figure 3)). Gaps are corrected and cuts are filled. The model has more than 580 layers (were worked manually to obtain an optimal delimitation) [15].

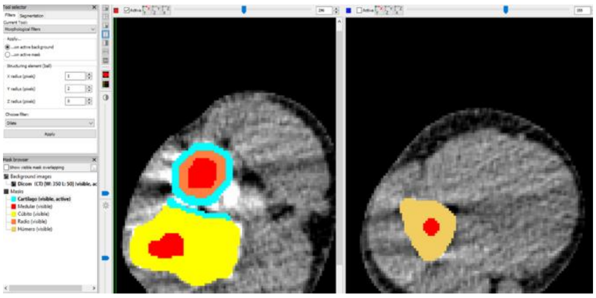


Figure 3. Creating masks for 3D elbow model in Scan IP®

Figure 4. Display of the 3D elbow model in the Scan IP® program

The 3D model is displayed (Figure 4). The model was saved in a computer-aided design software standard STL format that defines the geometry of 3D objects. It is worth mentioning that each mask was obtained in a separate STL format because the file size is very large. Due to the complexity of the file and the number of element its export in Parasolid format (*.x_t) [15].

The 3D mechanical modeling was developed through the conversion of the STL file by the SolidWorks® computer program. This type of file is universal in the language of numerical analysis programs. Likewise, it results in a completely solid 3D model of the elbow. It is also worth mentioning that the model it will be discretized automatically (Figure 5) [15].

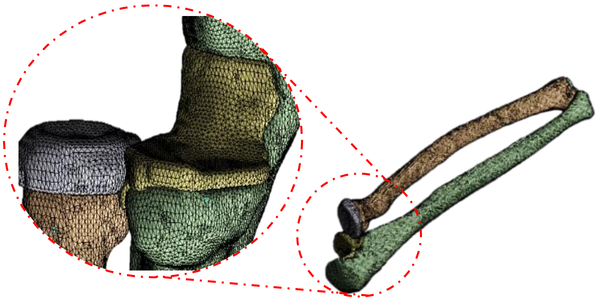


Figure 5. Discretization of the elbow bone system in 3D in ANSYS®

3. Mechanical considerations to carry out the numerical evaluation

The patient is considered to be in a condition of support (compression) of the forearms for this case study. This can occur in a person when doing a sporting activity (falling and leaning on the elbow) [9].

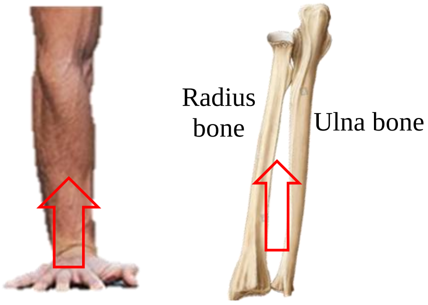


Figure 6. Graphic representation of the case study for compression

To determine the compression force (Fcom) it is important to consider some aspects that are presented. The radius bone transfers 60% of the total load, while the ulna bone 40% [16] (for an average person of 70 kg). So each arm will carry half the load (35 kg), the load coefficient $f_1 = 0.6$ and a dynamic coefficient of $f_2 = 1.2$ are taken into account, for the radius. While the ulna has a load coefficient $f_3 = 0.4$ and a dynamic coefficient of $f_4 = 1$. Finally, the acceleration due to gravity g = 9.81 m/s2 [16]. To obtain the total of the compression force of both bones, it is solved as follows [9]:

$$F_1com = m^* g * f_1 * f_2 = 148.33 \text{ N} \quad (1)$$

$$F_2com = m^* g * f_3 * f_4 = 54.94 \text{ N} \quad (2)$$

$$\sigma_y = F/A \quad (3)$$

$$\sigma_{1y} = 0.00678 \text{ MPa and } \sigma_{2y} = 0.00268 \text{ MPa}$$

4. Mechanical properties of the elbow bone system

The model, for the cases of study, was generated considering two components and three types of materials. The components are bone and cartilage. Bone is made up of two materials; cortical bone and trabecular bone. The tissue of the human bone system is an inhomogeneous and anisotropic material, which makes it difficult to have adequate samples for the determination of its mechanical properties. However, based on the literature and research, the values to be used can be seen in Table 1 [17].

Table 1.- Mechanical properties

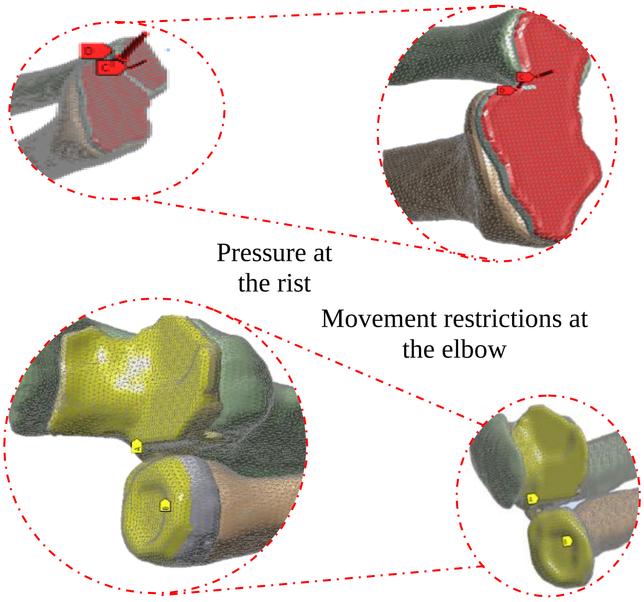
Material	Young's modulus	Poisson's ratio
Cortical bone	E = 18 GPa	$v = 0.31$
Trabecular bone	E = 400 MPa	$v = 0.26$
Cartilage	E = 1 GPa	$v = 0.40$

5. General conditions for the numerical evaluation

For all case studies, is stipulated that the analyses to be carried out are structural and static evaluations. As well as, the case studies are considered isotropic, homogeneous, continuous, and linear-elastic [9].

6. Discretization

The discretization of the model is performed by applying high-order solid elements (3D, 20 nodes, solid 186). It is composed of 6 degrees of freedom per node according to the ANSYS® literature. The discretization of the model was carried out in a free way, where 670 730 nodes and 163 elements were obtained (Figure 5) [18].



$$U_x = U_y = U_z = 0 \text{ and } Rot_x = Rot_y = Rot_z = 0$$

Figure 7. Movement restrictions and pressure

7. Conditions of movement restrictions and application of load

It is very important, when performing a numerical analysis by the computer program, to know exactly where external agents (pressures) and movement restrictions should be applied. Pressure load will be applied at the base of the rist (Figure 7) in a longitudinal manner. The movement restriction will be applied at the elbow. All movement will be restricted in all directions (no directional movements and no rotational movements). These conditions will be applied to areas of the bones [18].

8. Results of numerical evaluation

Three case studies were considered in this research work. Initially, the elbow system is considered healthy. Subsequently, two conditions of restoration of a fracture by means of two different types of screws are described.

8.1. Results for elbow system for sane condition

The most significant results are presented in terms of determining zones of a possible risk of failures (general displacement and von mises stress).

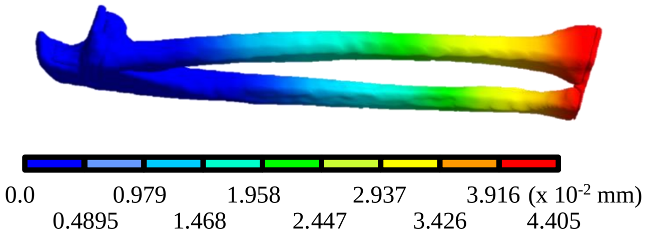


Figure 8. General displacement for elbow sane case

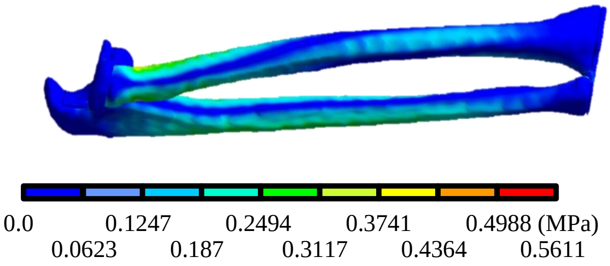


Figure 9. Von mises stress for elbow sane case

8.2. Results for elbow system with fracture

The elbow fracture is one of the main limitations that provides the stability of the humeral joint. This fracture type may be an isolated finding after elbow dislocation or part of a terrible elbow triad [19]. Elbow dislocation is a common injury, which represents 10% of injuries to said joint. Usually caused by sports or automobile accidents, some of the most frequent complications are stiffness and instability [20]. In this paper, three-screw fixation for coronoid fracture of the elbow will be discussed. The modeling of the titanium osteosynthesis screws was carried out according to the established norms. As well as, the position of the screws to treat the coronoid fracture of the radial head type 2 of the elbow. This based on the clinical case and using the model presented previously. Finally, the behavior of the fixing of the three screws in the case study will be known and a solution closer to reality will be obtained.

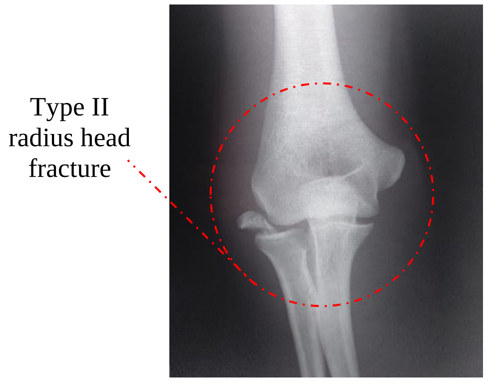


Figure 10. AP radiograph of the right elbow

The injury treatment is based on the radius head stabilization by means of open reduction of osteosynthesis material (in cases in which it is necessary to reduce). Figure 11 shows the fixation of three osteosynthesis screws for coronoid fracture of the radius head.

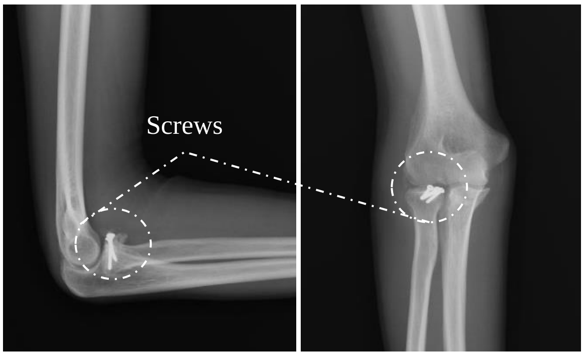


Figure 11. AP radiograph of the right elbow with screws

8.2.1. Results for fracture procedure with common cortical screws

The cortical screws type is commonly used as a fixation system for osteosynthesis (titanium 6AL-4V). They have a thread profile with special characteristics for fixation on cortical bone [21]. For the development of the screw,s it was performed by established norms. In Figure 12, you can see the finished design, it is worth mentioning that this design was made with the SolidWorks® computer program, with the specifications of Table 2. Two types were also designed of screws with different dimensions, due to the aforementioned clinical case study.

Another important aspect in the design of the osteosynthesis screw is the mechanical properties specified in Table 3. titanium 6AL-4V material was chosen due to its mechanical characteristics and a high degree of biocompatibility with the human body.

Table 2. Common cortical bone screw specification

Specification	2.0 mm ϕ	2.7 mm ϕ
Thread diameter	2.0 mm	2.7 mm
Length	16 mm	18 mm
Head diameter	4.0 mm	5.0 mm
Core diameter	1.3 mm	1.9 mm

Table 3. Titanium 6AL-4V mechanical properties

Variable	Value
Young's modulus	E = 104 GPa
Poisson ratio	ν = 0.33
Elastic limit	σ_y = 860 MPa

For fixing the screws into the model the 3D Builder® computer program is used, which facilitates the design, modification or visualization of a 3D model. The boundary conditions are repeated and the load is applied in the same regions as in the previous case.

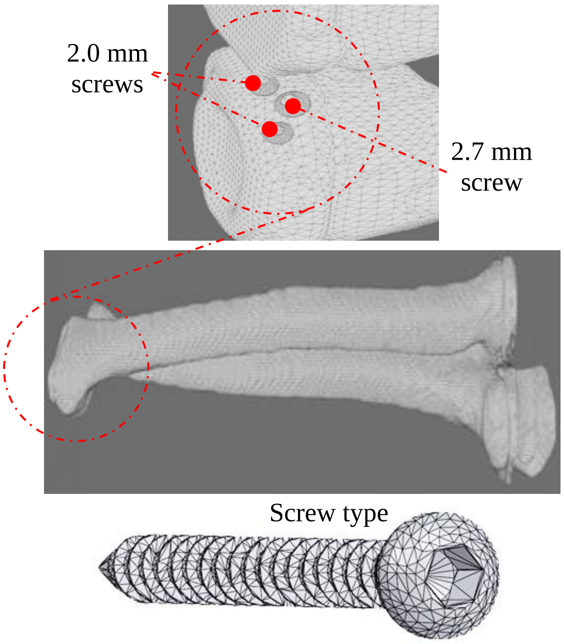


Figure 12. Fixation of titanium screws in the 3D model of the elbow in the 3D Builder® program

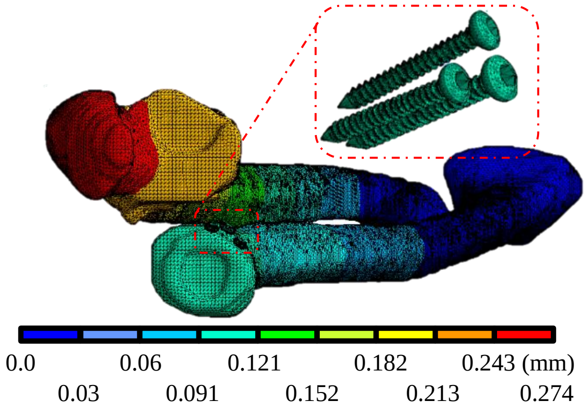


Figure 13. General displacement for elbow with fracture fixed with common screws

The most significant results are presented in terms of determining zones of a possible risk of failures (general displacement and von mises stress).

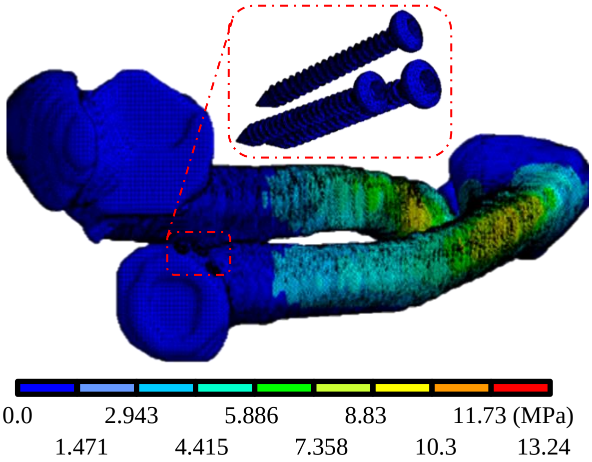


Figure 14. Von mises stress for elbow with fracture fixed with common screws

8.2.2. Results for fracture procedure with cancellous lag cortical screws

For this section, the use of cancellous lag screws will be used to treat the previously mentioned terrible triad of the elbow. These screws were designed according to the standards already established of orthopedics and traumatology (titanium 6AL-4V). Subsequently, the behavior of osteosynthesis devices will be seen to treat elbow fracture. The same 3D biomodel of the elbow that was used. The assembly of the three cancellous lag screws was similar to the common cortical screws. The numerical analysis conditions were applied as the two previous cases. This type of screw is usually used for internal fixation system and usually used for trabecular bone (in some cases for cortical bone). Mechanical properties can be seen in Table 3 [22]. In Table 4 it can be seen some specifications of the measurements that the cancellous lag screws must have. It is worth mentioning that two types of screw length were used, due to the position and the degree of inclination that the screws were placed and must have.

Table 4. Cancellous lag screw specifications

Specification	4.0a mm ϕ	4.0b mm ϕ
Thread diameter	4.0 mm	4.0 mm
Length	16 mm	18 mm
Head diameter	6.0 mm	6.0 mm
Core diameter	2.3 mm	2.3 mm
Pitch	1.75 mm	1.75 mm

For fixing the screws into the model the 3D Builder® computer program is used, which facilitates the design, modification, or visualization of a 3D model. The boundary conditions are repeated and the load is applied in the same regions as in the previous case. Once again the most significant results are presented in terms of determining zones of a possible risk of failures (general displacement and von mises stress) (Figure 16 and 17).

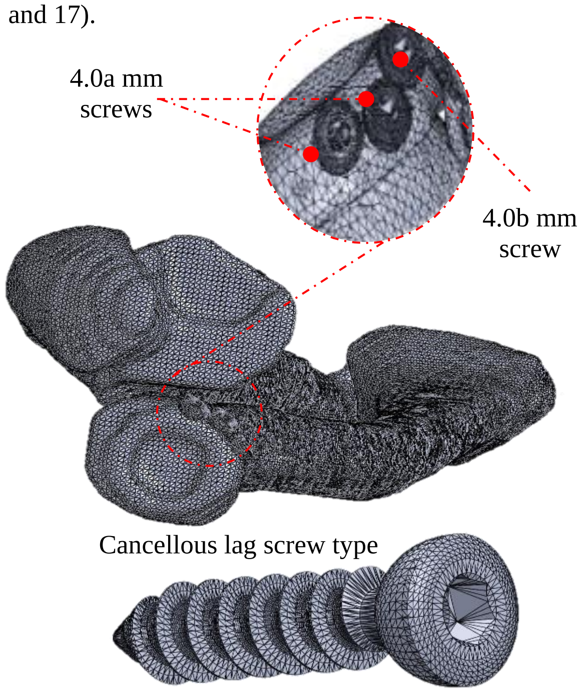


Figure 15. Fixation of Titanium cancellous lag screws in the 3D model of the elbow in the 3D Builder® program

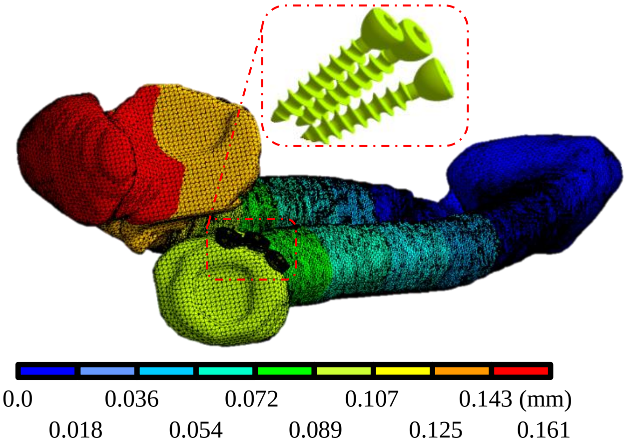


Figure 16. General displacement for elbow with fracture fixed with cancellous lag screws

8.2.3. Results for fracture procedure with 2 cancellous lag cortical screws

In this section the numerical evaluation is repeted for the procedure to fix an elbow fracture with two cancellous lag screws can be seen. All conisderation applied in this section are the same as the case of three cancelous screws. The position the the screws are the same as the two of top top of the cancellous lag screws configuration. Significant results are presented in terms of determining zones of a possible risk of failures by the general displacement and von mises stress in Figure 18 and 19.

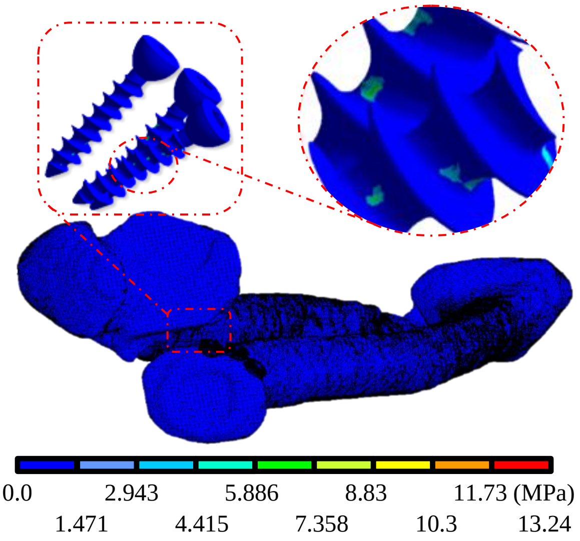


Figure 17. Von mises stress for elbow with fracture fixed with cancellous lag screws

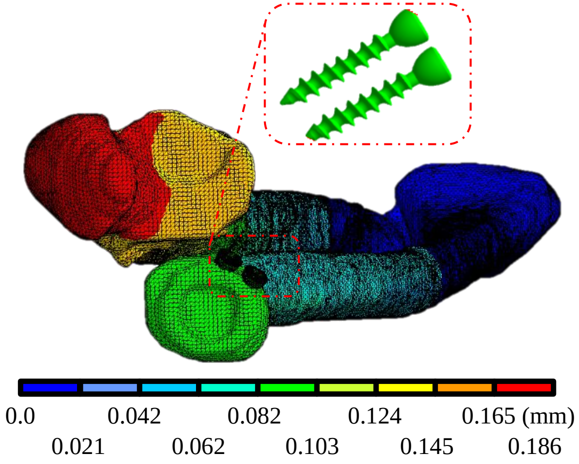


Figure 18. General displacement for elbow with fracture fixed with two cancellous lag screws

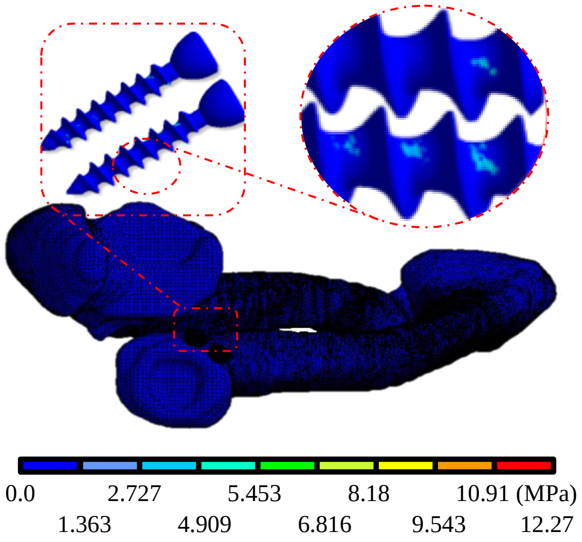


Figure 19. Von mises stress for elbow with fracture fixed with two cancellous lag screws

9. Conclusions

Table 5 shows the resume results for all cases of study in this investigation (values of the total elongation and the Von-Mises stress). A comparison of the three cases of study can be perform and it can be concluded if a general manner that the three cancellous lag and cortical screws are clinically and mechanically suitable for treating the aforementioned elbow coronoid fracture. Nevertheless, the values in the sane model are much lower than in the cases where screws are employed. The procedure where screws are used shows similarity. On the other hand, the results of the fixation of the two cancellous screws are observed (it is important to note that the position of the case study already seen was changed), these results show a similarity with the other results obtained from the fixations of three screws, Thus, it can be said that the fixation of the two cancellous screws (if is applied) in the elbow biomodel could be optimal and would not cause any change in the results of the clinical case mentioned in this investigation [18]. Additionally, the application of the Finite Element Method and the development of biomodels by tomography scan is an extremely powerful tool, which can help in the health sector. Also, it can be applied for the optimization of procedures and the design of better prostheses. Finally, numerical studies can provide a better understanding of how complicated mechanical systems work and can display better knowledge in small places.

Table 5. Results comparation

Case of study	**Displacement**	**Von Mises stress**
Sane	0.044 mm	0.5611MPa
3 common screws	0.274 mm	13.24 MPa
3 cancellous screws	0.161 mm	15.48 MPa
2 cancellous screws	0.186 mm	12.27 MPa

10. Acknowledgment

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