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Computer simulation of mechanical strength compared between straight and wave plates for femoral application through finite elements

Simulação computacional de resistência mecânica comparada entre placas reta e em onda para aplicação femoral por meio de elementos finitos

Simulación computacional de la resistencia mecánica comparativa entre placas rectas y onduladas para aplicación femoral mediante elementos finitos

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Abstract
The objective of this study was to evaluate, by means of computer simulation, the difference in mechanical strength between two plate models straight and wave used in femur fracture fixation, submitting both to a progressive static axial load. There are criteria to evaluate the yield strength of a material: Tresca, Von Mises and Mohr-Coulomb. In this study, the Von-Mises strain criterion theory was used because it is used in fatigue strength tests of ductile materials, in this case, stainless steel. This criterion, indicates that the yielding of a solid material begins when it reaches a critical stress value. The models were built computationally using 3D modeling software. The finite element mathematical method was used to evaluate the stress and strain curve, two elements considered fundamental to verify the behavior of the metal during the application of stress and the displacement of the plates, to thus evaluate the strength of each. The results obtained after the finite element analysis show that the plates do not reach the critical limit for yielding, but the straight plate absorbs 10 times more stress compared to the wave plate. The wave plate allows the conclusion that there is decomposition of the applied force. Both plates remain in the elastic regime with load up to 1000 N. The load is equivalent to the weight of the body and gravity. It was concluded that the axial force applied in the caudal direction decomposes into resulting ones compared to the straight plate, which absorbs all the load and may reach the critical limit for yielding before the wave plate.
Keywords: Finite element analysis; Femoral fractures; Musculoskeletal system**.**

Resumo
O objetivo deste estudo foi avaliar, por meio de simulação computacional, a diferença de resistência mecânica entre dois modelos de placas, reta e onda, usadas na fixação de fratura do fêmur, submetendo ambas a uma carga axial estática progressiva. Existem critérios para se avaliar o limite de escoamento de um material: Tresca; Von Mises e Mohr-Coulomb. Neste estudo, foi utilizada a teoria do critério da tensão de Von-Mises por ser utilizada em testes de resistência a fadiga de materiais dúcteis, neste caso, aço inoxidável. Este critério, indica que o escoamento de um material sólido se inicia quando atinge um valor crítico de tensão. Os modelos foram construídos computacionalmente utilizando o software de modelamento 3D. Foi utilizado o método matemático de elementos finitos para avaliar a curva de tensão e a deformação, dois elementos considerados fundamentais para verificar o comportamento do metal durante a aplicação de tensão e o deslocamento das placas, para, assim, avaliar a resistência de cada um. Os resultados

obtidos após a análise por elementos finitos demonstram que as placas não atingem o limite crítico para escoamento, porém, a placa reta absorve 10 vezes mais tensão em comparação com a onda. A placa onda permite concluir que há decomposição da força aplicada. Ambas as placas permanecem em regime elástico com carga até 1000 N. A carga equivale ao peso do corpo e da gravidade. Concluiu-se que a força axial aplicada no sentido caudal se decompõe em resultantes se comparada à placa reta, a qual absorve toda carga, podendo atingir o limite crítico para escoamento antes da placa onda.
Palavras-chave: Análise de elementos finitos; Fraturas femorais; Sistema musculoesquelético.

Resumen

El objetivo de este estudio fue evaluar, mediante simulación informática, la diferencia de resistencia mecánica entre dos modelos de placa recta y ondulada-utilizados en la fijación de fracturas de fémur, sometiendo a ambas a una carga axial estática progresiva. Existen criterios para evaluar el límite elástico de un material: Tresca, Von Mises y Mohr-Coulomb. En este estudio se utilizó la teoría del criterio de deformación de Von-Mises porque se utiliza en los ensayos de resistencia a la fatiga de materiales dúctiles, en este caso, el acero inoxidable. Este criterio indica que la cesión de un material sólido comienza cuando se alcanza un valor de tensión crítica. Los modelos se construyeron computacionalmente utilizando un software de modelado 3D. Se utilizó el método matemático de elementos finitos para evaluar la curva de tensiones y deformaciones, dos elementos considerados fundamentales para verificar el comportamiento del metal durante la aplicación de esfuerzos y el desplazamiento de las placas, para así evaluar la resistencia de cada una. Los resultados obtenidos tras el análisis de elementos finitos muestran que las placas no alcanzan el límite crítico de fluencia, sin embargo, la placa recta absorbe 10 veces más esfuerzos en comparación con la placa ondulada. La placa de ondas permite concluir que hay descomposición de la fuerza aplicada. Ambas placas permanecen en régimen elástico con una carga de hasta 1000 N. La carga es equivalente al peso del cuerpo y a la gravedad. Se concluyó que la fuerza axial aplicada en la dirección caudal se descompone en las resultantes en comparación con la placa recta, que absorbe toda la carga y puede alcanzar el límite crítico de cesión antes que la placa ondulada.
Palabras clave: Análisis por elementos finitos; Fracturas de fémur; Sistema musculoesquelético.

1. Introduction

The femur is the thigh bone, the longest and most voluminous of the human body. Among the fractures of long bones, femoral shaft fractures are one of the most frequent in men, as they are more exposed to traffic accidents (Pereira et al.,2020, Gutzeit et al., 2022). Appropriate treatment methods are necessary in order to rehabilitate patients as soon as possible, thus avoiding permanent sequelae and prolonged hospitalisations (Machado et al., 2021; Santos Júnior & Silva, 2021).

Several operative techniques are used for the treatment of femoral shaft fractures in an adult person. Among the techniques are the plate that fixes to the bone, the rod that fixes inside the bone and the external fixator for cases of muscle tissue injuries. The indication of the technique that can be plate, rod or fixator depends on the type of fracture, and the classification of this is based on the knowledge and experience of the surgeon (Dias & Gonçalves, 2021). As for the choice of surgical technique the wave plate is indicated in pseudoarthrosis and fragmented fractures and has biomechanical and biological advantages, as well as technical ease for performing the procedure. The intramedullary nail is the current standard for diaphyseal fractures of the femur (Uliana, et al., 2021), but it is specifically indicated for non-fragmented femur fractures, which present greater technical difficulties and require an image intensifier and greater skill from the surgeon. When talking about fractures, inadequate fixation may cause mobility at the focus of the fracture, making consolidation more difficult or even impossible.

In this sense, the use of a plate that may be straight or wave seems to present more advantages compared to the stem. Blatter and Weber (1990) presented a biomechanical study of the wave plate for absence of bone healing and its applicability in the treatment of synthesis material failures. The plate model proposed by the authors constituted a treatment option, being of easy access, low cost, ratifying the biological and mechanical advantages of the wave plate when compared to the conventional straight plate.

Recent studies have been using computer simulation and in vitro models in order to evaluate clinical situations where direct experimentation is limited due to ethical reasons. These studies show good reproducibility and reliability in their results

(Marongiu et al.,2020; Patel et al., 2018; Jorge et al., 2006). Given that stabilization is essential for fracture healing, several techniques are used for this purpose (Duncan & Turner, 1995; Kojima & Pires 2017). Among the techniques used to stabilize fractures, there are: plate, intramedullary rod or external fixator (Blatter & Weber,1990; Duncan & Turner, 1995; Kojima & Pires, 2017). The plate can be applied in two different forms: straight plate or wave. According to the above, this study aimed to test, through computer simulation, the difference in mechanical strength of two models of plates namely, a straight plate and another wave. For this, both were subjected to a progressive static axial load, according to failure criteria based on Von-Mises stress, to evaluate the difference in stress absorption (Hornik & Grün, 2014).

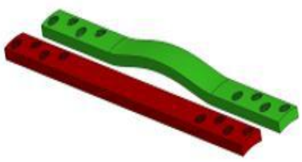
2. Methodology

This study was approved by the Ethics and Human Research Committee of the University of Caxias do Sul (UCS), under CAAE number 43614421.5.0000.5341º.

2.1 Model of the plate in two formats

Based on a model provided in the Unified Health System (SUS), a computer simulation was performed based on the characteristics of the Dynamic Compression Plate (DCP) in two formats, straight and wave, as shown in Figure 1. All elements were modeled according to the American Society for Testing and Materials - ASTM F138-13 (American Society for Testing and Materials, 2013). The simulated plate presents the following measures: 4.5 mm thick, 16 mm wide, 264 mm long, 158 mm distance between the innermost holes. For the computer simulation, the physical characteristics of stainless steel were considered, since this is the material used for orthopedic implants, having its biocompatibility tested and approved through tests and trials (American Society for Testing and Materials, 2013).

Figure 1. Plate models.



Source: Authors (2022).

As presented in Figure 1, a model was built for the molding of the LCP plate. So that it was possible to perform a computer simulation, a segment with four holes at each end was maintained. The formation of the curve with 10.0 mm of height started from the fourth (4th) hole, and the length of the wave was equivalent to 1/3 of the length of the plate.

2.2 Fracture simulation modeling

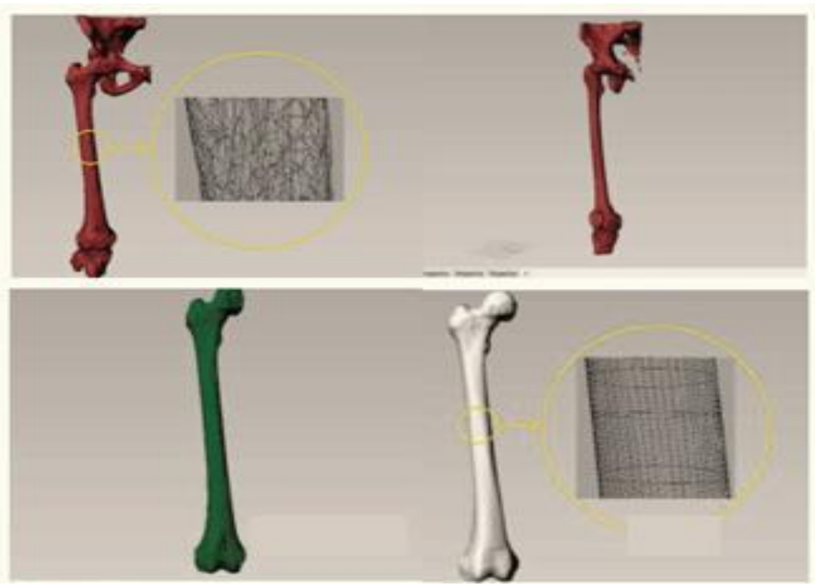
To simulate a 32C3-type femoral shaft fracture, the classification of the Association for Osteosynthesis/Association for the Study of Internal Fixation (AO/ASIF) (Matter, 1998) was considered. The construction of the 3D model was based on the computed tomography (CT) image of an adult patient, who volunteered and signed the informed consent for the study. Figure 2 shows the CT scan.

Figure 2 - Computed tomography image.

Source: Image Bank of Hospital São Camilo (2021).

Figure 2 illustrates a femur in CT scan to serve as a model for prototyping. Once the region of interest is defined in the Digital Imaging and Communications in Medicine (DICOM) image file processing program, one moves on to the export step to a format compatible with engineering programs. Export processes vary from program to program, but most allow conversion to Standard Triangle Language (STL) format, which is the standard input format for most Rapid Prototyping (RP) technologies. The files were initially used by the process, called Standard Triangle Language (STL). Its geometry is represented by a mesh of triangular elements, according to Figure 3, and, according to Kouhi, et al., (2008), the parameters of their files can generate meshes with larger or smaller triangles, which will directly influence the smoothness of the resulting mesh. The import result is shown in Figure 3.

Figure 3: Importing the STL file into 3D modelling and editing software.

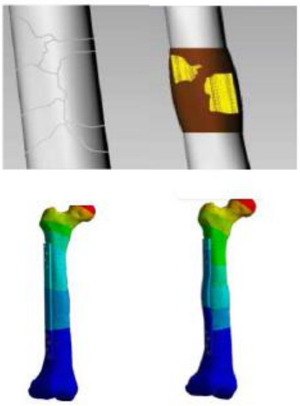


Source: Authors (2022).

After the editable model was ready, according to (Szejnfeld et al., 2007), the bone was divided into cortical and trabecular, considering a normal bone density of (76.93%) for a patient aged 50 years (Pereira et al.,2020). With the femur divided, a fracture simulation was created in the middle of the bone, dividing it into 8 parts, with the aim of simulating a type of multifragmented fracture for finite element testing.

Subsequently, based on the studies by Perren et al. (1969), callus was created in the fracture region with the same density as the intact bone. The two study models were evaluated by means of structural analysis. From the computer simulation, the plates were positioned close to the femur and fixed to the bone with 4 screws at each end, thus creating two complete assemblies, one with the straight plate and the other with the wave plate, as shown in Figure 4.

Figure 4: Simulation of fracture.



Source: Authors (2022).

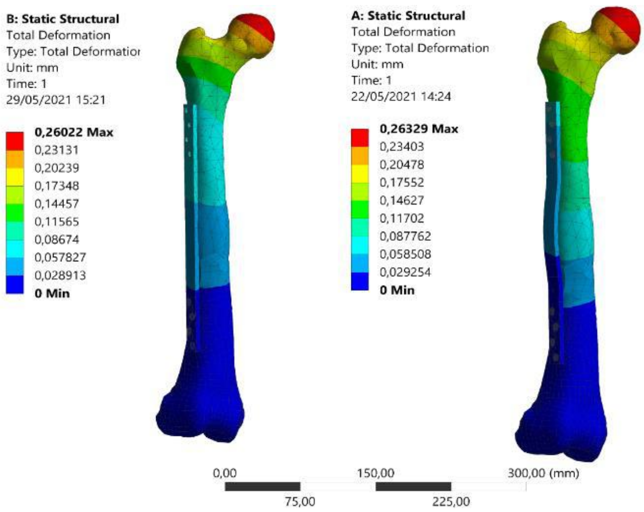
2.3 Finite elements analysis

According to Hornik and Grün, (2014); Nassiri, et al., (2013), the deformation of a solid (continuous) body with elastic properties, subject to elasticity conditions, expressed in a mathematical form using Finite Element theory (Patel et al., 2018; Cooper, et al., 2019). The Finite Element Method (FEM) is a mathematical analysis that consists of discretizing a continuous medium into small elements, maintaining the same properties as the original medium. These elements are described by differential equations and solved by mathematical models, so that the displacement and stress results are obtained (Orava et al., 2022). According to Viceconti (2019), bone fracture by overload can occur at any anatomical site. Those associated with reduced biomechanical competence (fragility fractures) occur most commonly in the wrist, followed by the ankle, spine and hip. The femur fracture is the one that involves the effects related to external load in a healthy patient. The model proposed here was analysed according to Von-Mises stress criteria (Hornik, & Grün, 2014). As already shown in Figure 1, it presents the femur bone which, in a common way, was used in both formats of the plate.

To perform the computational simulation, it was necessary to follow steps before the execution of the calculations performed in the structural analysis software, namely Ansys Workbench. Firstly, modelling of a tomographic image of femur of a volunteer was performed and a fracture was simulated in the middle of the bone in 8 parts. Solidworks modeling software was used to correct the femur faces (260 faces) in STL pattern (triangular mesh). From the image of the femur of a volunteer, the corrections of a tomography were made to create a model without flaws. Thus, two complete assemblies were performed: one with the straight plate and the other with the wave plate. Using Ansys Workbench software, the model was subdivided into smaller fragments (172,457) for mathematical calculations by finite elements. Based on the stress and strain graph, a comparison of progressive loads was made on the two assemblies in a static axial manner according to Von-Mises failure criteria (Hornik, & Grün, 2014).

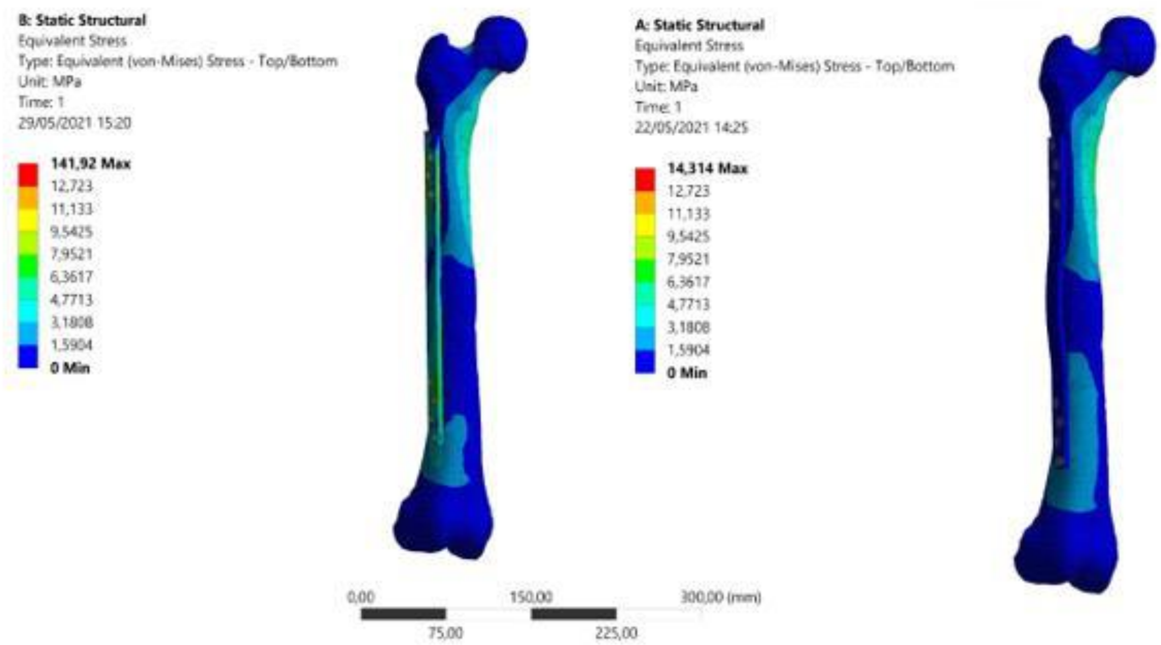
Figure 5 and 6 shows the simulations of the eccentric forces that occur physiologically in the femur diaphysis and also the behaviour of the plates in the femur. The numerical analysis of the finite element models was performed by simulating loads starting at 100 N and reaching 1000 N. For the simulation, an applied load was applied in the vertical direction. A static, vertical, axial load simulation was also performed using finite elements. According to the curve, stress and strain, the behavior of the straight plate and the wave plate was evaluated, which were subjected to the same progressive applied load to evaluate the force response applied in the same direction.

Figure 5 - Deformation of straight and wave plate.



Source: Authors (2022).

Figure - 6 Simulated loads.



Source: Authors (2022).

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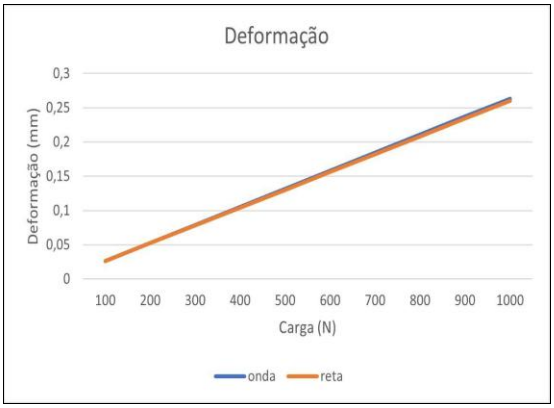
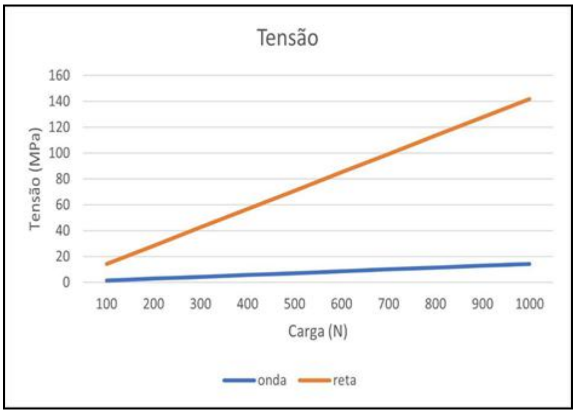
Graph 1 shows the comparison of the displacement in the straight plate and wave, and Graph 2 shows the stress applied to the two plates.

Graph 1: Displacement.



Source: Authors (2022).

Graph 2: Stress.



Source: Authors (2022).

From the graphs, it can be seen that they present close results regarding both plates, however, the maximum von-Mises stress (Hornik, & Grün, 2014) differs. The straight plate is subjected to a ten times higher stress with the possibility of fatigue earlier than the wave plate. However, the higher stress in the straight plate suggests that it can reach the yield strength first. The higher stress in the straight plate consequently may interfere with the stress limit supported at the focus of fracture, according to Perren et al., (1969). It is also observed that by increasing the tension in the straight plate, we will reach the yield limit, and that this may interfere in bone healing.

Furthermore, we should take into consideration the phase of bone callus formation, which goes through 4 phases, namely: 1) the hemorrhagic phase; 2) hematoma; 3) the fibrous phase; 4) and, finally, bone healing. There is also the variable moment of bone healing which depends on the tension at the fracture site (Perren et al., 1969). Thus, it is convenient that there is relative stability with the wave plate, because besides allowing adequate strain in the multifragmentary fracture, it also allows the division of tension between the bone and the plate.

Therefore, for the implant to present a satisfactory result after surgery, it is necessary that it allows bearable tension so that the bone can reach complete healing. From the beginning of the consolidation, the minimum mobility of the fragments (strain) in the focus and the bearable tension may stimulate the formation of the bone callus. In this respect, according to Perren et al. (1969), the implant should allow sufficient tension in the bone so that it can support the formation of bone callus until complete healing is achieved. This tenuous line of mobility at the focus (Strain) and local tension may accelerate the fracture or impede consolidation if there is greater mobility and tension than the bone can support. If we increase the tension in the straight plate, we will reach the yield limit, and this will interfere in bone healing with the variable of the moment in which the healing phase is with greater tension at the fracture focus. It is also observed that the straight plate, as it absorbs 10 times more tension, may reach first the yield limit and, consequently, fatigue, and thus prevent successful bone healing.

However, there is a need to perform an analysis of the fatigue of plates with greater load by means of computer simulations before clinical trials in vivo. The studies performed were static with load up to 1000 N, that is, equivalent to 100 kg, with the patient stationary. It requires an increase in the moving load until the yield limit is reached.

3. Results and Discussion

The method chosen for this study advocated the use of a computer model that sought to simulate the eccentric forces that occur physiologically in the femoral shaft. This study simulated the treatment of a 32C3-type diaphyseal fracture of the femur fixed with a straight plate and wave, taking into account the classification of the Association for Osteosynthesis/Association for the Study of Internal Fixation (AO/ASIF). After building the 3D model, which was based on the computed tomography (CT) image of an adult patient who volunteered and signed the informed consent form, the study was initiated. After the editable model was ready and based on specific literature, Szejnfeld et al. (2007) divided the bone into cortical and trabecular, considering a normal bone density of (76.93%) for a patient aged 50 years. With the femur divided, a fracture simulation was created in the middle of the femur, dividing it into 8 parts, as shown in figures 2 and 3.

Subsequently, according to specific literature, a callus was created in the fracture region. The two models proposed by the study were tested by means of computer simulation, thus creating two complete assemblies, one with the straight plate and the other with the wave plate, as already demonstrated in Figure 3. The results were obtained after numerical analysis of the finite element models, through load simulation, starting at 100N and reaching 1000N (dividing by 9.81, obtaining a variation from 10.19kg to 101.93kg). Applying an applied load in the vertical direction, with static simulation, i.e., stationary, with axial load, vertical downwards, by means of the mathematical method (FEM), it is concluded that, the straight plate absorbs greater stress, specifically up to 10 times more than the wave plate. The wave plate absorbs 10% of the stress if compared to the straight plate, with division of stress with the bone. Both plates remain in the elastic regime with loading up to 1000 N.

According to Kojima, et al., (2010), the mechanical influence of the length of the curve in 1/3 of the plate and height of 10 mm presents different result compared to 20 mm height regarding stiffness and maximum load. The placement of a polyamide block simulating graft under the curve increases the possibility of load and stiffness, producing a mechanism called tension band, which, in our study, suggests load division according to computer simulation (Kojima, et al., 2010). After numerical analysis, it was observed, as a result of Graph 1, that there was no change of elastic regime related to the static load up to 1000 N. On the other hand, in Graph 2, there was significant deviation related to higher stress absorption by the straight plate up to 10 times more.

No fatigue related to the load was observed in the plates. In both there was permanence of the elastic regime with progressive load from 100 N up to 1000 N (Applied Load) and static axial load. However, the load in the wave plate presented tension division between the bone and the plate. It is observed that in the wave plate there is compression and tensile force, and in the bone there is compression force during loading, equivalent to body weight and gravity. From this modelling, we can consider that the wave plate presents a different result from the straight plate, with load deviation in the wave plate and, therefore, a lower risk of failure.

The process of fracture healing involves bone contact between fragments, stability and an adequate blood supply so that it is not impaired (Jorge et al., 2006). Interruption in the bone healing process leads to delayed union or pseudoarthrosis. The causes of pseudoarthrosis are related to a situation in which the fracture does not show radiographic evidence of progression of the healing process, indicated by sclerosis at the fracture extremities, the presence of a hiatus, absent or hypertrophic callus, and persistence or enlargement of the fracture line (Reis, et al., 2005; Weber & Cech, 1976). According to Weber and Cech (1976), pseudoarthroses can be classified into viable and non-viable, according to the fragments' vitality conditions. Viable pseudoarthroses, which are also known as hypervascular or hypertrophic, present rich blood supply at the fragment extremity and are capable of biological reaction. Generally, they are caused by lack of stability, which generates excessive mobility at the fracture site. They are solved with bone stabilization, which can be obtained with a plate, intramedullary rod or external fixator (Angelini, 2001; Marongiu; et al., 2020; kojima & Pires; 2017).

One of the options for the treatment of diaphyseal pseudoarthrosis is the wave plate (Jorge; et al., 2006; Blatter & Weber, 1990), since the wave plate causes the plate to move away from the cortical bone, giving the osteosynthesis biological and mechanical advantages (Blatter & Weber, 1990). Unlike the conventional straight plate, which, to have efficient fixation, needs intimate contact between the plate and the bone, creating a surface and friction between both (Jorge et al.,2006; Perren et al., 1969; Izzawati et al., 2019).

According to Kojima, et al., (2010), the presence of the wave in the plate favourably alters the biomechanical conditions at the site of diaphyseal pseudoarthrosis. Also, for the authors, the compression forces occur through the medial cortical and traction through the lateral cortical, i.e., if there is a failure in the medial cortical, there will be a great effort in flexion in the plate placed in the lateral cortical. The presence of the wave displaces the plate from the bone and directs the compression forces towards the focus of the pseudoarthrosis, thus transferring the compression force from the medial cortical to the lateral cortical, i.e., the plate begins to support tensile force and not bending force (Kojima &, Pires, 2017; Angelini,2001). In this study, the difference between the straight and wave plate, as simulated by finite elements, suggests deviation of the direction of the force in x and y resultant in the wave plate, without the need to interpose graft to modify this effect by the division of tension between bone and plate.

In the tests performed by Angelini (2001), Kojima, et al., (2010) and Kojima and Pires (2017), the Dynamic Compression Plate (DCP) was used in a plastic deformation regime in which dimensional change occurs and with model characteristics favourable to fatigue as holes in all extension, acute angulation and manual modelling, causing the onset of a permanent deformation resulting from the displacement of atoms or molecules to new positions with irreversible deformation of the metal. Several studies demonstrate that the treatment of pseudoarthrosis of the femoral shaft with a wave plate presents excellent results regarding consolidation, even in more complicated situations, that is, the response is positive both from the mechanical and biological point of view (Jorge et al., 2006; Kojima, et al.,, 2010; Ring et al., 1997; Khanfour & Zakzouk, 2012).

However, although the technique and wave-plate moulding are widely discussed and indicated for the treatment of multifragmented femoral fractures and diaphyseal pseudarthrosis, there is no physical model of the wave-plate available on the market, that is, despite the technique having recognition in the literature with several published papers, laboratory and in vitro tests, and computer simulations, Thus, it is necessary to mold the plate in a surgical block, which may cause some possible failures in the material, since when molding the plate, it will be exposed to permanent deformation resulting from the displacement of atoms or molecules to new positions in the reticulate.

4. Final Considerations

Given the above and from the study presented here, we can consider that the wave plate presents a different result from the straight plate regarding stress and, therefore, lower risk of failure. Thus, it is suggested the development of a wave plate that has the characteristics suggested in this study, being produced and worked in an elastic regime, presenting a wave in the plate since its manufacture in stainless steel, without presenting holes in the total extension, considering only holes at the ends, thus avoiding points of vulnerability of the material.

From this study, we can consider that the plate in wave presents a different result from the straight plate with respect to load sharing and, therefore, lower risk of failure. Thus, it is suggested the development of a plate that has the characteristics evaluated in this study, being produced and worked in an elastic regime, presenting a wave in the plate since its manufacture in stainless steel, without presenting holes in the total extension, thus to avoid points of vulnerability of the material.

5. Limitations of the study

There is a need of further comparative studies to titanium metal and also dynamic studies that approach the body weight load in motion and all directions of acting forces, such as rotation, flexion and overload until fatigue. In this study, the density considered as the focus of fracture was equal to the density of normal bone; however, it is suggested that simulations be carried out considering other bone densities, for example, the femur of a smoker, overweight and with lower density in the fracture region due to the callus formation.

Another limitation of the study was the impossibility of testing on a cadaver, as there was no action of the musculature with neutralization of forces, as the study requires load movement. The in vivo studies have an ethical limitation because the suggested wave plate does not exist and requires evaluation in animals, although the technique is widely used with the existing straight plate and considered in our study as not ideal. The need for mathematical calculations using finite elements, although excellent for simulating real-life situations, depends on specific software and a qualified engineer; however, as this professional does not have clinical experience, a multidisciplinary team is required.

It is also important to say that in this study, the difference between screws regarding the stability of the assembly was not evaluated, because the locking in the plate (locking) can present a difference between titanium and steel, as well as the screw without locking (without locking) in the plate.

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