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Original Article

Mind the gap between the fracture line and the length of the working area: a 2-D finite element analysis using an extramedullary fixation model☆

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ABSTRACT

Objective: To determine the ideal working area for a simple transverse fracture line treated with a bridge plate.

Methods: A 2-D finite element analysis of a hypothetical femur was performed for the quantitative evaluation of a large-fragment titanium alloy locking plate based on the precept of relative stability in a case of a simple transverse diaphyseal fracture. Two simulations (one case of strain and another case of stress distribution) were analyzed in three unique situations according to the von Mises stress theory. Load distributions were observed when the bone was subjected to a single vertical load of 1000 N.

Results: The longer the length of the implant flexion, which coincided with the working area of the plate, the greater the flexion of the implant. The highest concentrations of stress on the plate occurred in the region around the screws closest to the bone gap. The closer the screws to the fracture site, the greater the demands on the plate.

Conclusion: When using a large-fragment titanium alloy locking plate to stabilize a simple transverse fracture based on the precept of relative stability (bridge plate), there must be considerable distance between the proximal and distal screws closest to the fracture line. The farther away this fixation is, the lower the stress on the plate and the greater the dissipation of force in the form of deflection.

☆ Study conducted at the Serviço de Ortopedia e Traumatologia Prof. Nova Monteiro, Hospital Municipal Miguel Couto, Rio de Janeiro, RJ, Brazil.

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Observe a distância entre a linha de fratura e o comprimento da área de trabalho: Análise bidimensional de elementos finitos em modelo de fixação extramedular

Palavras-chave:
Análise de elementos finitos
Osteossíntese
Placas ósseas
Regeneração óssea

R E S U M O

Objetivo: Determinar qual é a área de trabalho ideal em uma fratura de traço simples transverso tratada com placa em ponte.

Métodos: Foi feita uma análise bidimensional de elementos finitos em um fêmur hipotético para avaliação quantitativa de uma placa bloqueada para grandes fragmentos feita de liga de titânio, usada com o princípio de estabilidade relativa em uma fratura diafisária de traço simples e transverso. Foram analisadas duas simulações, uma de deformação e outra de distribuição de tensão, de acordo com a teoria de von Mises, em três situações distintas. Foram observadas as distribuições de carga quando o osso foi submetido a uma carga monotônica vertical de 1.000 N.

Resultados: Quanto maior o comprimento de flexão do implante, o que coincidiu com a área de trabalho da placa, maior a flexão dele. A maior concentração de tensão na placa foi observada na região dos parafusos mais próximos do defeito ósseo. Quanto mais próximos os parafusos do foco de fratura, maior a demanda sobre a placa.

Conclusão: Ao usar uma placa bloqueada para grandes fragmentos feita de liga de titânio para estabilizar uma fratura de traço simples e transverso pelo princípio de estabilidade relativa (placa em ponte), a distância entre os parafusos mais próximos do traço de fratura proximal e distalmente deve ser longa. Quanto mais distante essa fixação, menor a concentração de tensão na placa e maior a dissipação de esforços na forma de deflexão.

Introduction

In the skeletal system, the biomechanical environment plays a fundamental role in bone repair and remodeling, in order to meet functional requirements.[1] In this context, the relationship between physical factors and cellular responses is critical; the success of the consolidation process requires the maintenance of appropriate forces on a bone capable of responding adequately.[2] The concept of mechano-regulation, that describes the ratio of the relative deviation of the fracture edges *versus* the width of the initial defect and determines the morphological characteristics of bone repair, has been known for some time.[3] Correct interpretation and application of this concept allows the orthopedic surgeon to choose the best fixation precept and aids in making important therapeutic decisions, such as the reduction method and the type of implant.

Regardless of the fixation precept, in bone tissue repair, the important mechanical characteristics of the final product are its strength and stiffness. Primary healing, usually observed after anatomical reduction of fracture focus and rigid internal fixation with plate and screws (absolute stability), resembles the physiological remodeling of bone; it is a slow process. Its indication is absolute in the management of articular fractures, although its use has now been abandoned in most diaphyseal fractures. As several studies have demonstrated, the axial and cyclic compression forces applied to the diaphysis of the long bones improve healing through the formation of a larger cartilaginous callus and of an earlier bone bridge, maintaining and protecting the fracture reduction, and allowing a certain degree elastic deformation (relative stability) that appears to be quite rational.[4–7] The amount of bone tissue formation depends on this interfragmentary stress.[3,5,8]

Mechanically, when compared with osteosynthesis with an interfragmentary compression plate, extramedullary fixation with a bridge plate undergoes increased flexion and torsion loads, resulting in high stresses on the implant. Therefore, predicting the mechanical performance of a fixation device is paramount and depends on several factors. One of the most important factors is the estimated length of the working area during fracture fixation, defined by the distance between the screws closest to the proximal and distal fracture focus.[9] It is believed that the stress is lower on the plate when the working area is smaller.[10]

Ideally, in a simple transverse line fracture, it is expected that the interfragmentary mobility will be equally divided between the implant and the opposite side of the bone, when an axial load is exerted. However, this type of behavior has been evaluated only under absolute stability, but not in a relative stability model. The present study aimed to examine the stresses and deformations during gradual flexion on a locking plate secured under the precept of relative stability in a simple transverse line fracture. Three configurations of screw placement were envisioned, and the working area varied in distance from the fracture focus. The authors aimed to determine the ideal working area for a simple transverse line fracture treated with a bridge plate.

Methods

Computational model

A 2D finite element analysis of a hypothetical femur was performed for the quantitative analysis of a locking plate secured under the relative stability precept in a simple transverse line diaphyseal fracture. The bone model used was virtually mapped from a femur through a computational finite element study. Once the femur was mapped, stress distributions were observed throughout the bone when it was subjected to a monotonic vertical load of 1000 N (Fig. 1).[11]

Characterization of the bone gap and the plate

A 2-mm bone defect (fracture line) was made, mimicking a simple transverse line. Straight, large-fragment plates with locked screws were used in the study. The mechanical properties of the metal parts (plate and screws) were adopted from a titanium alloy (Ti6Al4V), in accordance with ASTM-T136. Under the study conditions, the plate reacted as a rigid, single body, both in relation to the screws as to the bone in the areas farthest from the bone defect. The goal was to limit the study to the space between the two closest screws superiorly and inferiorly to the fracture line (plate working area). Fig. 2 illustrates the study design.

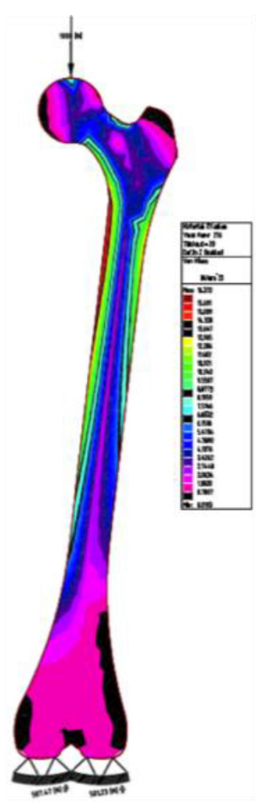

Fig. 1 – von Mises stress distribution (expressed in N/mm^2) in an intact femur model, mapped virtually through computational finite element.[11] Note that the maximum recorded effort was 16,372 N/mm^2 in the subtrochanteric region.

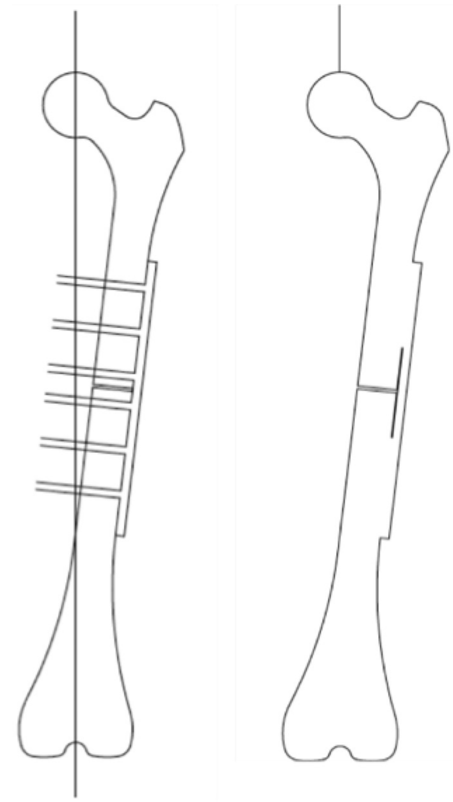

Fig. 2 – In order to study just the working area of the plate, a 2 D model was built in which the plate reacted as a rigid body to the screws and bone in its distal regions. The leftmost image shows the distribution of the screws in the working area simulations. The left image shows the rigid-body behavior of the plate-screws-bone, outside the analyzed region.

Simulations

Two simulations were analyzed according to the von Mises theory, one for deformation and one for stress distribution, in three different situations. Deformation was analyzed on the hypothetical femur; the load was applied on the femoral head. The von Mises stress analysis is based on the determination of the distortion energy associated with alterations in the shape of the tested material.

The three following situations were tested:

Situation 1 – Small plate working area, with the screws more distal to the proximal fragment and more proximal to the distal fragment, placed at 5 mm from the fracture line.

Situation 2 – Intermediate plate working area, with the screws more distal to the proximal fragment and more proximal to the distal fragment, placed at 25 mm from the fracture line. Situation 3 – Large plate working area, with the screws more distal to the proximal fragment and more proximal to the distal fragment, placed at 45 mm from the fracture line.

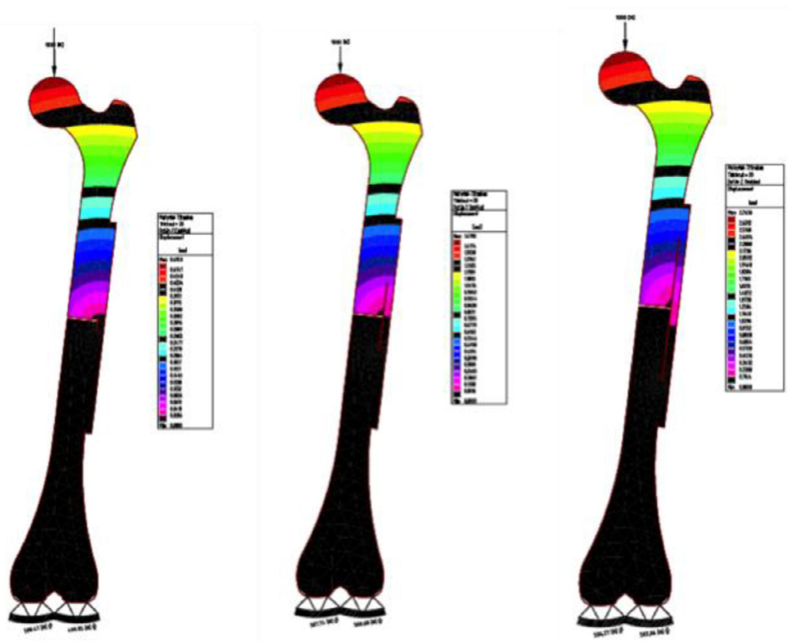

Fig. 3 – Deformation simulation – a load of 1000 N was applied to the femoral head and an amount of flexion on the plate was observed. The larger the virtual length of the plate, the greater its flexion.

Results

Deformation

In order to calculate plate deflection, the bone defect (fracture line) was discarded, so that only the free deformation of the extramedullary implant would be assessed. All calculations presented a linear behavior.

The maximum deformation values observed at the upper point of the femoral head (load application point) ranged from 0.49 mm in Situation 1–2.74 mm in Situation 3. This means that the larger the fictitious flexion length of the implant, which coincided with the working area of the plate, the greater the flexion of the implant. Fig. 3 presents the simulation of deformation.

Stress

The maximum von Mises stress values did not show variations greater than 10%. The highest concentration of plate stress was observed in the region of the screws closest to the bone gap. The closer the screws to the fracture focus, the greater the stress on the plate. The stress simulation is shown in Fig. 4.

Discussion

The mechanical assay of fractured long bones with fixation devices is a good opportunity to experimentally test the structural properties of the bone fixation construct. The successful treatment of fractures depends on rapid bone regeneration, which requires proper maintenance of the forces acting on bone. As a rule, the basic forces of compression, shear, torsion, and flexion produce predictable bone behaviors; these forces are the base of experiments aiming to observe, as an example, the rigidity of a fixation.[12] The applicability and relevance of these experiments aim to improve fracture fixation and to minimize biomechanical disorders that may interfere negatively with the consolidation process.

In the present study, a 2D finite element analysis was performed in a hypothetical femoral model, aiming to determine the ideal working area in a simple transverse line fracture treated with a bridge plate. The femur underwent a monotonic vertical load of 1000 N, which simulated the compression force undergone by this bone during the monopodal support of a 96 kg individual. A 2 mm gap was created to simulate a simple and transverse fracture line; therefore, the expected percentage deformation ratio would be elevated.[3] Other studies have used and validated the same defect size to study the resistance of implants used for bone fixation.[3,13,14] The implant used in this experimental model was a large fragment titanium-alloy locking plate (bridge plate), in accordance with the relative stability precept. Studies have shown the benefits of using titanium implants other than those made of stainless steel, especially regarding their lower modulus of elasticity (practically half that of stainless steel), which reduces the rigidity of the fixation and allows sufficient interfragmentary deformation on the plate.[9,15]

It was observed that the closer the screws are to the fracture line (the smaller the working area), the higher the concentration of stress on the plate and the lower the dissipation of stress in the form of deflection. This creates conditions that can lead to fatigue due to the high cycle observed in metallic implants. On the contrary, the larger the working area (the more distant the screws to the fracture line), the lower the concentration of stress on the plate and the greater the dissipation of stress in the form of deflection, which improves implant durability and minimizes fatigue.[16] To the best of the

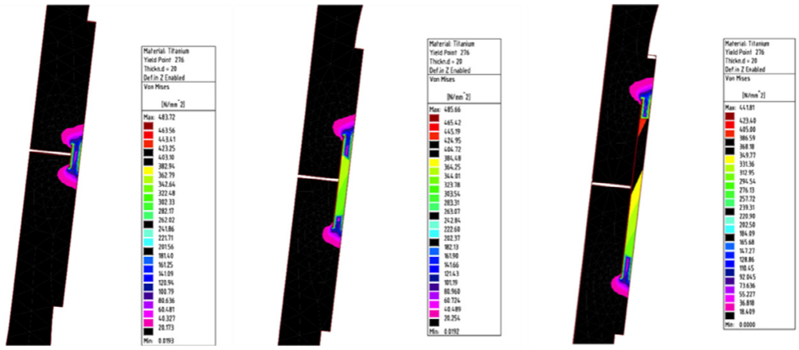

Fig. 4 – Stress simulation – the highest stress concentration on the plate occurred in the screws closest to the bone gap, in a constant way, with similar stress. Note that, as the working area increased, the stress on the plate in the region without screws was reduced – the maximum von Mises stress was 483.72 N/mm^2 for Situation 1, 485.66 N/mm^2 for Situation 2, and 441.81 N/mm^2 for Situation 3. The closer the screws to the fracture focus, the greater the stress on the plate.

authors' knowledge, despite being empirically examined by many, this observation had not been demonstrated in a finite element analysis model.

Regarding the biomechanical aspect, there are large differences between extramedullary osteosynthesis with a plate for a small gap secured according to the precepts of absolute stability, and that of relative stability. In the former, it is believed that the stress is lower on the plate when the working area is small; it can now be said that in the latter, the ideal scenario is a large working area. Thus, the greater the elastic deformation capacity of the bridge plate, the lower the risk of rupture or fatigue.[17] In artificial femur models, Hoffmeier et al.[18] and Kanchanomai et al.[19] observed a reduction in the surface stress of stainless steel and titanium locked plates, the larger the working area of the implant. This demonstrates that the fatigue behavior is dependent on the working area, among other factors related to the osteosynthesis technique.

Study limitations

A limitation of the present investigation was the use of a 2D model instead of a 3D, as the latter is considered to be ideal in finite element analysis. Although it was possible to determine the ideal working area in a simple transverse line fracture treated with a bridge plate, it was not possible to quantify it in real or percentage values. As an association was clearly observed between the two assessed phenomena (deformation and stress), it can be inferred that the working area should be large when the line is simple and the percentage deformation is high. The authors believe that the point of encounter between a lower von Mises stress and greater plate deformation will numerically represent the ideal distance between the screws closest to the proximal and distal fracture line. Further studies should be conducted to develop the 3D multibody finite element analysis, using a real femoral model to accurately quantify the distance between the screws proximally and distally closer to the fracture line (working area) under the same conditions of the current study.

Another limitation of the study was the stress in a single plane. The authors followed the original concept of mechanoregulation, which considered only the longitudinal percentage deformation along the mechanical axis of the bone.[3] Aro et al.[20] demonstrated that passive and active axial dynamization with an external fixator in stable fractures (small defects) and unstable fractures (large defects) produces an increase in quantity and a better distribution of the periosteal callus, uniting the main bone fragments. Other researchers have demonstrated that axial and cyclic compression forces applied to the diaphysis of long bones improve healing through the formation of a larger cartilaginous callus and an earlier bone bridge.[4–7] Three-dimensional analyzes, however, have revealed the existence of a complex and multidirectional deformation in the fracture focus.[14] Future studies that associate efforts in other planes may aid in the definition of a triple stress state system for assessing various osteosyntheses.

Finally, other factors related to the quality of osteosynthesis, such as geometry, modeling conditions, and implant materials and properties models were not evaluated in the present study.[18,21,22] It is known, for example, that the resistance of implants depends more on the material they are made from than on the working area determined by the surgeon.[18,21] Although not perfectly understood, it has been shown that with stainless steel plates the working area has no significant effect on the strength and rigidity of the construct, being more durable than those made of titanium. For this reason, Hoffmeier et al.[18] suggest the use of stainless steel plates for the treatment of unstable fractures, especially if some degree of healing delay is expected. Nonetheless, in the present study, the computational model used to simulate the mechanical conditions of a titanium-alloy locking plate (Ti6Al4V) used to secure a small bone defect (2 mm) did not characterize a situation of instability. Thus, even though it is known that with titanium plates the larger the working area, the lower the rigidity of the construction, the present findings allowed the conclusion that, under the conditions studied, a larger working area produces less stress concentration on the plate, which can significantly extend its lifespan.

Conclusion

When using a large fragment titanium-alloy locking plate to stabilize a simple transverse line fracture under the relative stability precept (bridge plate), the distance between the screws closest to the proximal and distal fracture line should be far apart. The more distant this fixation, the lower the concentration of stress on the plate and the greater the dissipation of efforts in the form of deflection.

Conflicts of interest

The authors declare no conflicts of interest.

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