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The Impact of Geometry on the Mechanical Stability of Plates for Internal Bone Fixation

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ABSTRACT

The aim of this work is to investigate the impact of geometry on the mechanical stability of characteristic structural solutions of plates for internal bone fixation using the finite element method (FEM). Based on the realistic construction of plates for internal bone fixation, 3D geometric and FEM models were formed, and then structural analysis was carried out in the CAD/CAE system CATIA V5. Five different types of plates for internal bone fixation were tested under two types of loads: axial pressure and torque in the case of application to the femur. During the structural analysis, stresses and displacements were monitored at characteristic points of the structure. The most attention was paid to the relative displacements of the bone model fragments, because the stiffness of the plates for the internal fixation of the bone was determined based on them. At the end of the paper, the results of all analyzed plates are presented, their mutual comparison as well as the conclusion in which, based on everything done, it was stated which plate would be the most favorable solution for a given case of bone fracture.

Keywords: internal fixation plate, von Mises stress, stiffness, interfragmentary displacements, FEM analysis.

INTRODUCTION

A fracture is a complete break in the continuity of a bone, which is most often caused by the action of an external force on the bone. It can be spontaneous and traumatic. A spontaneous fracture occurs as a result of increased bone fragility caused by pathological changes (bone tumors, metastases, osteoporosis, osteomyelitis). Fracture fixation secures the broken bone segments in the desired position for healing. Different methods of fixation can be adopted depending on the severity and location of the fracture. One of the most commonly used methods of fixation is the use of internal plates and screws that can be made of different biocompatible materials [1]. Plates for internal fixation of bone fractures have been used for more than 100 years and are the most common implants in internal fixation [2], showing many advantages, such as sufficient stability, resistance to stretching, resistance to compression, resistance to shear, resistance to torsion and resistance to bending [3]. Plate fixation technology results in less soft tissue injury than open reduction, but also has a higher rate of fracture malformations and an increased possibility of local pressure on the soft tissues [4–6]. To meet the demands of bone healing in an appropriate biomechanical microenvironment, the structure and materials of bone plates have undergone a long evolution.

With advances in the understanding of the factors that influence fracture healing, the design of fracture fixation plates is undergoing continuous innovations. The design philosophy of internal bone fixation plates can be classified into three categories: compression plates, limited contact plates, and biological fixation plates [7].

Before people understood the importance of micromotions for fracture healing, internal bone fixation plates were designed to fix the fracture ends as stably as possible [8].

According to this principle, coapteur plates, tension plates and dynamic compression plates (DCP) were created, which can be collectively called compression plates [9].

In their studies, many authors investigated various factors that influence fracture healing, so Perren et al. [10] found that excessive contact between the internal fixation plate and the cortical bone impedes blood flow and causes necrosis of the cortical bone beneath the plate, which is believed to be the main cause of local osteoporosis. Based on this knowledge, the locking compression plate (LCP) was developed. However, Field et al. [11] compared the actual contact area between DCP and limited-contact dynamic compression plate (LC-DCP) with cortical bone under the plate. It was found that there was essentially no significant difference between the two designs. Jain et al. [12] measured cortical blood flow using laser Doppler flowmetry of canine tibiae fixed with DCP or LC-DCP and the results obtained were consistent with those of Field et al. [11]. After that, the point contact fixator (PC-Fixator) was developed, in which the contact surface between the plate and the cortical bone is reduced due to the point contact. Tepić et al. [13] investigated the therapeutic efficacy of a standardized oblique tibial fracture in sheep treated with DCP and PC-fixator and found that PC-fixator can help the tibia to recover its mechanical function faster. Haas et al. [14] treated a forearm fracture with a PC-fixator. Compared to the conventional plate, fracture fixation with the PC-Fixator has multiple advantages: easier surgery, shorter healing time and fewer surgical complications.

A good treatment effect has been achieved in the fixation of bone fractures with conventional internal fixation plates made of stainless steel or titanium alloy. The main goal of bone fracture fixation with conventional plates is to provide the necessary mechanical stability to the ends of the fracture, i.e. to avoid any microdisplacement of the fracture. The aim of this paper is to investigate the influence of geometry on the mechanical stability of plates for internal bone fixation applied to the femur in the case of an open fracture under load from axial pressure and torque. Construction parameters that are taken into account for the analysis are: the value of the maximum von Mises stresses, inter-fragment displacements at certain fracture points, as well as the stiffness of the fixator.

DEVELOPMENT OF CAD/FEM MODEL

The software package CATIA V5 was used for the development of the CAD/FEM model of plates for internal bone fixation. The first thing that needs to be done when creating a volumetric model of the internal bone fixation assembly is the individual creation of a model of its constituent components.

The bone model is first modeled in such a way that it is divided into two parts and the distance between the bones is adjusted to be 5 mm. This value was obtained on the basis of data from orthopedic practice, and corresponds to the length of an open fracture with a minor bone structure defect [15,16]. The bone for which the analysis was made is the femur, for which plates are often applied for internal fixation of the bone, especially in case of fractures where repositioning of fragments is required. Different materials are used for the bone model material. The most commonly used materials are PVC (juvidur), wood, aluminum, copper, etc. In this investigation, beech wood with known mechanical characteristics, similar to human bone, was used for the bone model material (Table 1) [17,18].

After the bone model, it is necessary to form the other plates models. Three types of plates were selected for analysis: Narrow Dynamic Compression Plate, Broad Dynamic Compression Plate and Narrow Locking Compression Plate (Figure 1).

Also, for narrow and broad plates, an analysis was performed for two different types of cross-section, with full and limited contact (Fig. 2).

Narrow DCP is 12 mm wide, 199 mm long and 4 mm thick, while the number of screw holes is 12. Broad DCP is the same length and thickness as the narrow plate, while its width is 16.5

Table 1. Mechanical property of beech wood

Property	Mark	Value
Normal modulus of elasticity	E_{11}	2060 MPa
Transversal modulus of elasticity	E_{22}	1120 MPa
Longitudinal modulus of elasticity	E_{33}	15400 MPa
Poisson’s coefficient in x’y’ plane	ν_{12}	0.66
Poisson’s coefficient in x’z’ plane	ν_{13}	0.055
Poisson’s coefficient in y’z’ plane	ν_{23}	0.037
Sliding modulus in x’y’ plane	G_{11}	450 MPa
Sliding modulus in x’z’ plane	G_{22}	1530 MPa
Sliding modulus in y’z’ plane	G_{33}	1170 MPa
Density	ρ	740 kg/m^3

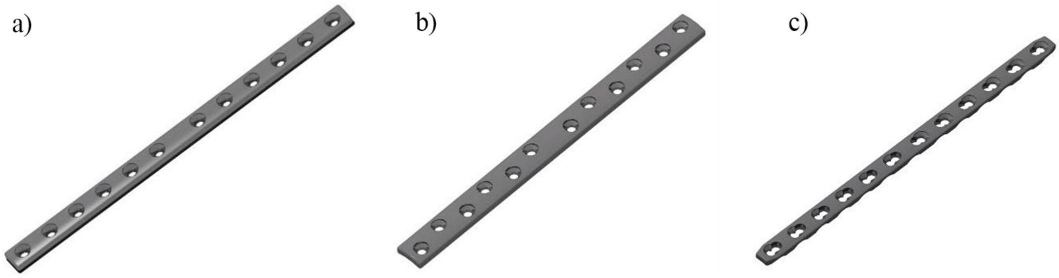


Figure 1. The types of analyzed plates, (a) Narrow DCP, (b) Broad DCP, (c) Narrow LCP

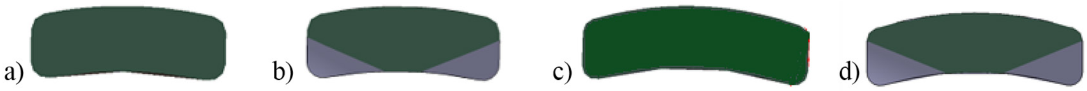


Figure 2. The cross-section of plates, (a) Narrow DCP, (b) Narrow LC-DCP, (c) Broad DCP, (d) Broad LC-DCP

mm. Also, in the case of a broad plate, the screw holes are placed alternately in such a way that they are 2 mm away from the axis of symmetry. Narrow LCP has the same width and thickness as the narrow plate, while its length is 215 mm. The advantage of this plate compared to the previous two is that it can be applied with ordinary screws and locking head screws. Two cases were analysed for this plate. The first case is with locking head screws, while the second case is with a combination of locking and non-locking screws. In the second case of Narrow LCP plate analysis, six locking head screws and four standard head screws were selected. The material of the plates is stainless steel 1.4441. The connection of the plates to the bone model is achieved with cortical screws with a standard head and a locking head. The standard head screw is assigned a thread with a nominal diameter of 5.5 mm and a pitch of 2 mm, while the locking head screw is assigned a thread with a nominal diameter of 3.5 mm and a pitch of 1.25 mm. The locking head screw is shorter than a standard head screw and has a tip that allows it to tap itself during application. This screw, in addition to the thread on the body, also has a thread on the countersunk head, which allows it to be locked in the fixation plate, which also has a thread in the hole. In order to prevent compression on the bone during the application of this screw, it is necessary that the pitch of the threads on the body and on the head are equal. The material of the screws is titanium alloy Ti6Al4V.

The volume model of the internal bone fixation assembly was created in the Assembly Design module, and then FEM modelling was performed in the Generative Structural Analysis module. The first step in the formation of the FEM model is the discretization and selection of finite elements, where finite elements of the parabolic type (TE10) tetrahedron were used. The finite element size for the plate and screws was 1 mm with an Absolute sag value of 0.1 mm, while for the bone model a finite element size of 3 mm was taken with an Absolute sag value of 0.3 mm.

After the discretization, the next step is to define the connections between the components of the internal fixation assembly. The connection between the screws and the bone model is defined as a screw connection (Figure 3a). Contact connections are defined between the screw head and the plate, as well as between the plate and the bone model (Figure 3b).

After defining the connections, the supports on the internal bone fixation model were defined, which also represents a constraints on the model. When it comes to axial compressive load, then on the distal part of the bone model it is necessary to place a joint connection to simulate a human joint. To achieve this, a virtual joint was created using the Smooth Virtual Part option. The joint enables rotation in all directions around a defined point in space, which represents the center of the sphere, and prevents translation. On the other hand, a constraints was set on the proximal part of the bone model using the User-defined Restraint option, which enables all three rotations and translation in the axial direction, while the translations in the remaining two directions were disabled. During torsional loading, the proximal part of the bone model is clamped using the Clamp option, while a joint is placed on the distal part of the bone that allows only rotation around one axis to avoid bending of the bone and the connection.

a) b)

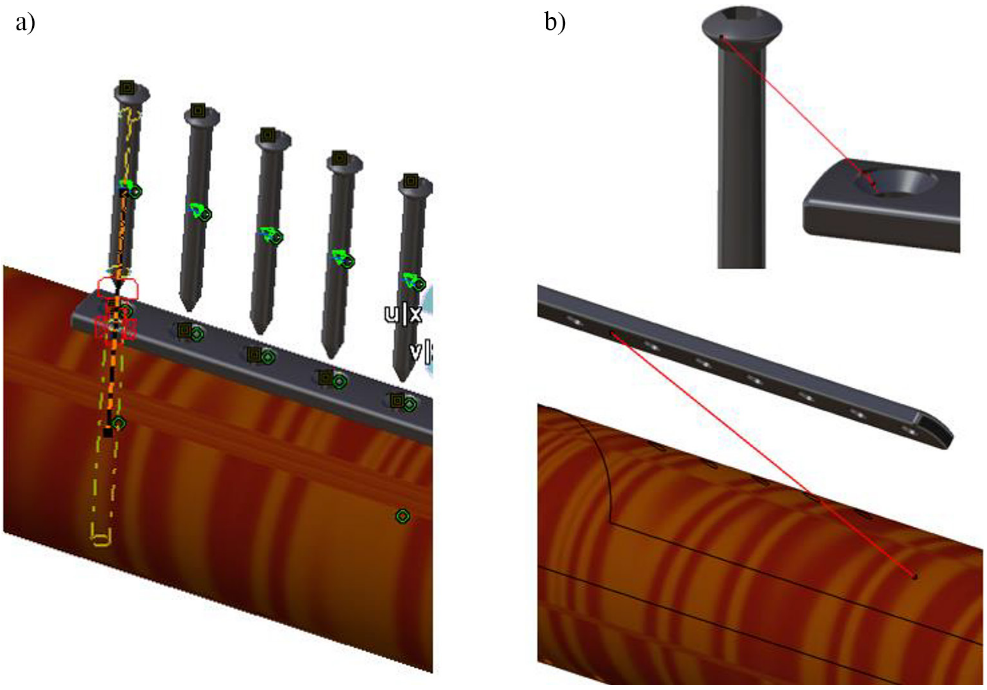
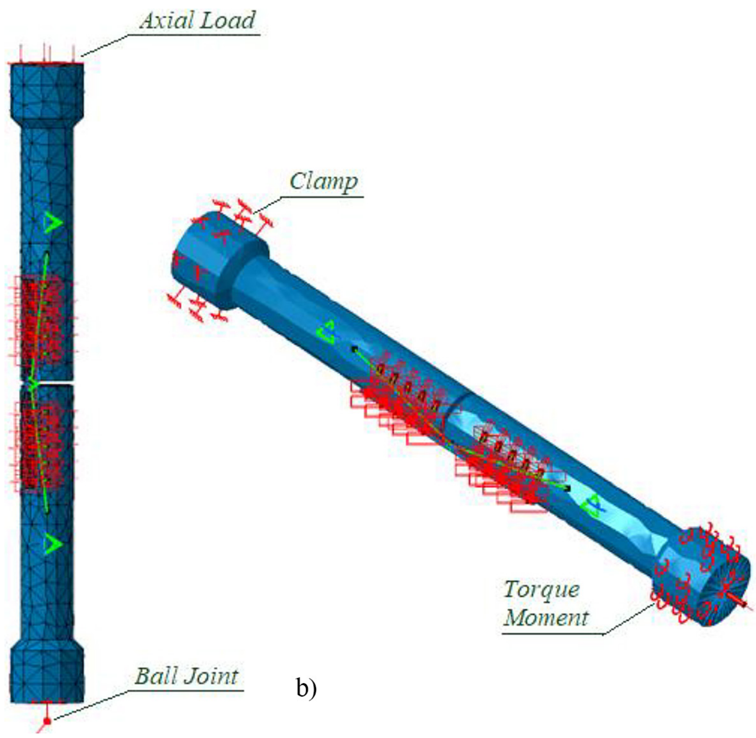


Figure 3. Defining connections: (a) Bolt tightening connection, (b) contact connection

After defining the constraints, the load is defined on the internal bone fixation model (Fig. 4). Axial load is applied to the proximal part of the bone model in the form of surface load, which is expressed by means of forces that are distributed over a certain surface. Based on the recommendations of orthopedists from clinical practice, and guided by the research of other authors in this field, the value of the maximum axial load by compressive force during the FEM analysis for this type of internal fixation was adopted as 600 N [19], while the value of 5 Nm was adopted for the torque [20].

After the FEM modeling of the internal fixation assembly in the CATIA V5 software package, a structural analysis was performed for the given loads.



a) b)

Figure 4. Defining constraints and loads: (a) axial load, (b) torque

Determination of stress, displacement, and stiffness

During the structural analysis, the values of the principal and von Mises stresses generated on the plate and in the screw-bone contact were monitored. The value of the equivalent uniaxial stress or von Mises stress is often used in solid mechanics, and is defined as [21, 22, 23]:

$$\sigma_e = \sigma_{vm} = \sqrt{3J_2} =$$

$$= \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

where: J_2 – the second invariant of stress deviator, σ_1, σ_2, σ_3 – the principal stresses.

Also, the values of interfragmentary displacement were monitored, on the basis of which fracture stiffness is defined. The displacements in the x, y and z directions of a pair of adjacent points on the end planes of the proximal and distal segments at the fracture site are determined, for which the resulting relative displacement vector (Rmax) has a maximum value (Figure 7). Total stiffness is defined as the ratio between the load and the resulting relative displacement of the observed pair of points. [24, 25, 26]:

- for the case of axial load

$$C_{pp} = \frac{F_P}{R} = \frac{F_p}{\sqrt{\left(r_{D(x)}\right)^2 + \left(r_{D(y)}\right)^2 + \left(r_{D(z)}\right)^2}}$$

- for the case of torque

$$C_{pu} = \frac{M_u}{R} = \frac{M_u}{\sqrt{\left(r_{D(x)}\right)^2 + \left(r_{D(y)}\right)^2 + \left(r_{D(z)}\right)^2}}$$

where: F_p – the axial pressure force, M_u – the torque moment, R – the resultant vector of the relative displacement, $r_{D(x)}$, $r_{D(y)}$, $r_{D(z)}$ – the relative displacements of points of bone model segments in x, y and z direction [mm].

The relative displacements of the pair ($r_{D(x)}$, $r_{D(y)}$, $r_{D(z)}$) of the observed points on the end planes of the proximal (upper) and distal (lower) segments of the bone model in the x, y and z directions are determined as [27, 28, 29]:

$$r_{D(x)} = D_{p(x)} - D_{d(x)}$$

$$r_{D(y)} = D_{p(y)} - D_{d(y)}$$

$$r_{D(z)} = D_{p(z)} - D_{d(z)}$$

where: $D_{p(x)}$, $D_{p(y)}$, $D_{p(z)}$ – the displacement of the proximal segment of the bone model in the x, y and z direction [mm].
$D_{d(x)}$, $D_{d(y)}$, $D_{d(z)}$ – the displacements of the distal segment of the bone model in the x, y and z directions [mm]

RESULTS

The von Mises stress distribution on the construction of the internal fixator is shown in Figure 5 for the load from axial pressure (a) and torque (b).

In addition to monitoring the von Mises stress on the construction of the internal fixator, the von Mises stress values were also monitored at the bone-screw connection, at the place of the most loaded screw (Fig. 6).

Also, in addition to the von Mises stress, the displacement vectors of the points at maximum load were monitored (Fig. 7), where the direction and intensity of the displacement vectors of the analyzed points can be clearly observed. Also, the values of the displacement vector components of the observed points on the fracture were

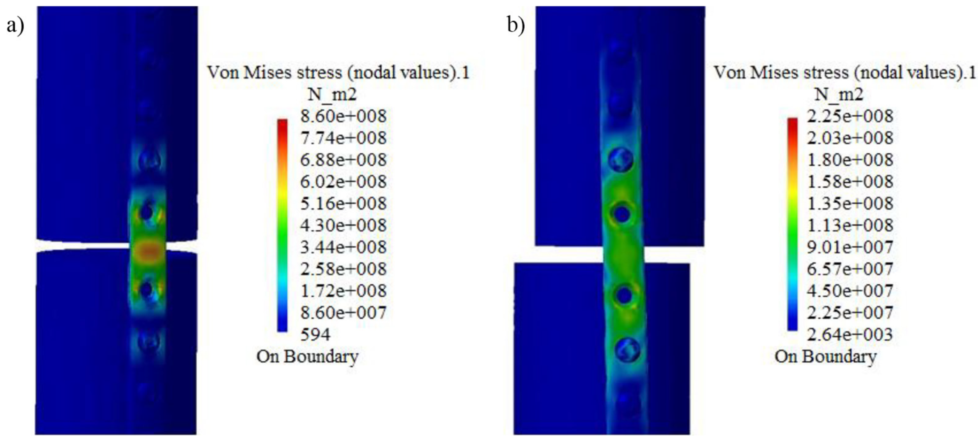


Figure 5. Von Mises stress on a Narrow LC-DCP: (a) axial load, (b) torque

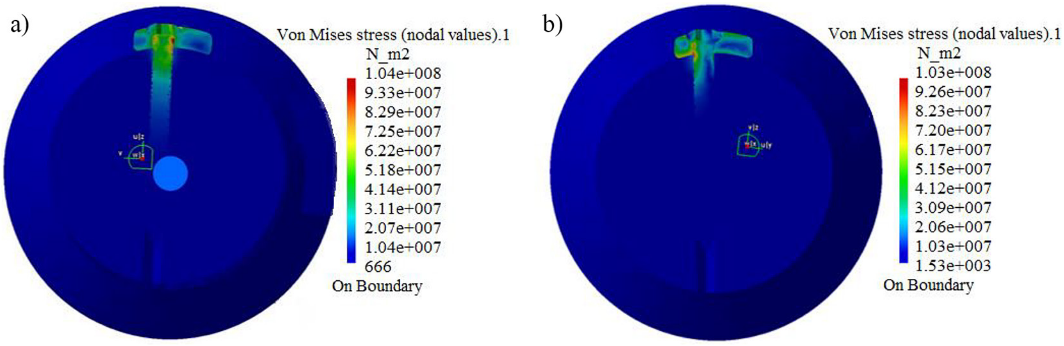


Figure 6. Von Mises stress on the cross-section of the most loaded bolt of a Broad DCP: (a) axial load, (b) torque

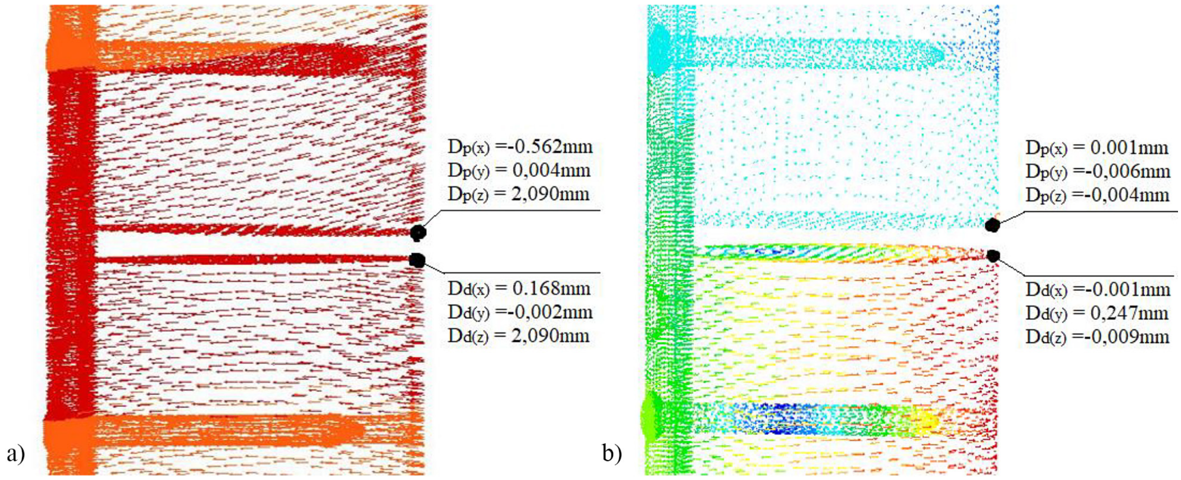


Figure 7. Point displacement vectors for the case of a Broad DCP: a) axial load, b) torque

Table 2. Results of plate analysis

Type of plate	Type of load	Relative displacement of the observed pair of points (mm)	Von Mises stress on the plate (MPa)	Von Mises stress in screw-bone contact (MPa)	Axial / Torsional Stiffness (N/mm)/ (Nm/mm)
Narrow DCP	Axial load	1.42	456	143	422.5
	Torque	0.54	96.4	118	9.26
Narrow LC-DCP	Axial load	1.86	556	187	322.58
	Torque	0.59	116	89	8.47
Broad DCP	Axial load	0.73	250	95	821.92
	Torque	0.3	74	87	16.38
Broad LC-DCP	Axial load	1.03	422	110	582.52
	Torque	0.37	93	95	13.51
Narrow LCP-I	Axial load	2.6	595	123	230.77
	Torque	0.76	95	174	6.58
Narrow LCP-II	Axial load	2.08	580	180	288.46
	Torque	0.63	91	149	7.94

determined, on the basis of which the relative displacements were determined.

The results of the structural analysis of plates for internal bone fixation, when loaded with axial pressure and torque, are shown in Table 2.

DISCUSSION

Many mechanical and clinical studies of plate shapes and screw positions have been conducted with the aim of improving biomechanical stability as well as preventing loosening and reducing loss after fracture fixation [30, 31, 32]. Our study analyzed the influence of geometry on the mechanical stability of plates for internal bone fixation using numerical methods. For this purpose, five different types of plates for internal bone fixation were tested under two types of loads: axial pressure and torque in the case of application to the femur.

Looking at the results of the structural analysis for narrow plates (Narrow DCP and Narrow LC-DCP), we can notice that by reducing the contact between the plate and the bone for both load cases, there is an increase in the displacement at the fracture site in the amount of 31% for axial load, and 9% for torque. Also, there is an increase in the Von Mises stress on the plate, in the amount of 22% for axial load, and 21% for torque, while at the point of screw-bone contact we have an increase in Von Mises stress in the amount of 31% for axial load, and a reduction of 25% for torque. As a result of the increased displacements at the fracture site, we have a reduced stiffness of the plates in the amount of 24% for axial load, and 9% for torque.

Looking at the results of the structural analysis for Broad plates (Broad DCP and Broad LC-DCP), similar conclusions can be drawn as for Narrow plates. The increase in displacement at the fracture point for both load cases is 41% for axial loads and 23% for torque. Also, Von Mises stresses on the plate increased by 69% for axial load and 26% for torque, while at the point of screw-bone contact, unlike narrow plates, in both cases of loading we have an increase in Von Mises stress and that in the amount of 16% for axial load, and 9% for torque. As a result of the increased movements at the fracture site, we have a reduced stiffness of the plates in the amount of 29% for axial load, and 17% for torque.

Looking at the results of the structural analysis for plates with a combination of screws (Narrow LCP-I and Narrow LCP-II), we can notice that the geometry of the screw significantly affects the mechanical stability of the plates. The combination of standard screws and locking screws for both load cases results in a reduction of movement at the load point, in the amount of 20% for axial load and 17% for torque. On the other hand, we have a slight reduction of Von Mises stress on the plate, in the amount of 2.5% for axial load, and 4% for torque, while at the point of screw-bone contact, we have a similar situation as with narrow plates, i.e. we have an increase in Von Mises stress in the amount of 46% for axial loading, and a decrease of 14% for torque. As a result of the reduced displacement at the fracture site, we have an increase in the stiffness of the plates in the amount of 25% for axial load and 20% for torque.

Analyzing the results of all three types of plates in this case of using plates for internal fixation in long bones, an important factor is the stability of the plate-bone connection itself, where we can state that the Broad DCP gives the best results, but this does not necessarily mean that it is also the best in terms of bone fracture healing itself, because it has contact with the bone itself along its entire length and prevents bone circulation under the plate.

Analyzing the results of the stiffness of the plates as well as the relative transverse displacements at the point of fracture, the Broad DCP also has the best results, while the Narrow LCP-I, in the case of the configuration with locking head screws had the lowest stiffness and the highest relative displacement of the fragments.

Likewise, it can be noted that the cross-section at the point of maximum stress has a significant influence on the stability of the observed bone and plate assembly. This turned out to be particularly negative in the case of narrow plates, where the cross-section of the plate was significantly weakened due to reduced contact. Also, the stability is affected by the arrangement of the screws, where the arrangement of the screws displaced from the very axis of the plate proved to be definitely better, which can only be done with wide plates.

CONCLUSION

In this paper, which aimed to analyze different constructional solutions of plates for internal bone fixation in terms of the most even stress picture and clinically permissible displacements at the fracture site, it was necessary to pay attention to other parameters of optimal bone healing, such as bone circulation, the easier the application, the less bone damage, etc.

Taking into account all of the above, the best solution for the analyzed case of fixation of the femur bone in an open fracture is a Broad LC-DCP, because it represents a compromise between a smaller area of contact with the bone and a not too weakened cross-section, and yet on the other hand displacements are small and within the limits of clinically permitted.

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