Finite Element Analysis of Different Titanium Plates for Internal Fixation of Fractures of the Mandibular Condylar Neck

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Purpose: The purpose of the present study is to compare the performance of 4 titanium miniplates (alpha, kappa, rhomboidal, and trapezoidal) used for the fixation of condylar neck fractures by implementing computational finite element analysis.

Methods: Three-dimensional models of the plates were used to reduce a virtually created condylar neck fracture in a mandible obtained from a computed tomography scan of a healthy adult. The developed models were analyzed, making use of the finite element method under 2 loading scenarios: a reduced postoperative bite force of 135 N and a clenching force of 500 N were examined. The plating designs’ performance was assessed based on displacements along the fracture area, bone strains, and plate stresses.

Results: For a loading limited to 135 N, all 4 plates offer an adequate fixation with a small risk of screw loosening for the rhomboidal and trapezoidal plates. For an applied force of 500 N, the alpha and kappa plates showed better results, distributing more homogeneously the strains in the bone and offering better rigidity.

Conclusions: These findings implicate that the alpha and kappa plates performed better when bigger loads are applied. On the other hand, the trapezoidal and rhomboidal plates are not recommended for condylar fractures, especially if bigger functional loads are expected.

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Surgical treatment of displaced condylar neck and base fractures using open reduction and internal fixation (ORIF) is a common treatment option. Meta-analysis has shown that ORIF of displaced condylar neck and base fractures demonstrates better clinical and functional results than nonsurgical treatment.1

Biomechanical analysis of the mandibular condylar process was performed by Meyer et al.2 This work indicated that 2 plates should be placed parallel to the posterior border of the ramus and below and parallel to the sigmoid notch for a successful osteosynthesis of the condylar neck and base fractures. However, a narrow condylar process can be incompatible with the application of these 2 plates.3

In addition, there is evidence from experimental studies and finite element models that the bone density decreases and strain distribution increases in the thinner mandible regions, such as the condyle...
neck or in atrophic mandibles. This could result in altered biomechanical behavior of the bone for condylar neck fractures compared with subcondylar fractures, despite the fact that these areas are in proximity to each other. Therefore, the 3-dimensional plates developed for use in the condylar area, such as kappa plates, alpha plates, or trapezoid-shaped plates, can have different results when used in the condylar neck instead of the subcondylar area.

Failure after ORIF of the condylar process has been reported to be present, especially in condylar neck fractures. Vajgel et al reported 1 condylar neck fracture in a cohort group of 32 patients with condylar fractures, where plate loosening appeared 10 weeks after surgery. Smolka et al found 2 failures after ORIF of condylar neck fractures in a group of 10 patients with 7 subcondylar and 3 condylar neck fractures.

Finite element analysis (FEA) is a numerical technique that simulates the mechanical behaviors of loaded structures. FEA has widely been used to explore the behavior of plating systems in maxillofacial trauma. In mandibular condylar process fracture cases, several different plating techniques, such as 2 straight plates, strut plate, lambda plate, trapezoid-shaped plate, and delta plate systems, have been evaluated using FEA.

All these numerical investigations using FEA have been performed for the fixation of subcondylar fractures. Consequently, there is no knowledge about the fixation rigidity or performance of different plating systems for condylar neck fractures. The aim of the present study is to evaluate stresses in various types of plates placed for a virtually created unilateral condylar neck fracture of the mandible. A computed tomography (CT)-based 3-dimensional finite element model of a patient is used to select an optimal plating system and to compare the findings with those of the studies about fractures in the subcondylar area.

Materials and Methods

This study was approved by the institutional review board of the University Hospital of Munich (LMU Munich, Germany; No. 19-783).

Building the 3D Geometry

A high-resolution CT of a healthy human mandible with a slice step of 0.62 mm was implemented to generate and segment a 3-dimensional surface representation of the mandibular bone (MIMICS 14; Materialise, Leuven, Belgium). A condylar neck fracture (high subcondylar fracture) was introduced to the model’s left side by implementing the 3-Matic software (Materialise, Leuven, Belgium). The fracture line was designed according to the recent AO CMF classification system above the level of the sigmoid notch line with an angle of 36.5° from posterior caudal to anterior cranial. The 2 fracture surfaces lie 0.2 mm apart to provide a more realistic representation of the actual condition.

The 3-dimensional representations of 4 plating designs (alpha, kappa, rhomboidal, and trapezoidal plates) were developed. Initially, the aforementioned geometries of the miniplates were provided by the manufacturer (KLS Martin, Tuttlingen, Germany) and were ultimately incorporated in the model following the same processing method as the mandibular model. In addition, 6 × 2 mm nonthreaded screws were designed by the researchers according to the manufacturer’s specifications and were used to fix the 1-mm thick miniplates to the bone.

Boundary and Loading Conditions

All 4 geometries, 1 for each plate, were placed under the same loading and boundary conditions. Although a reduction of the post-traumatic bite force was reported, an agreement on the magnitude of this bite force has not been achieved. For this reason, we examined each plating technique for 2 distinct scenarios: a load of 500 N simulating the maximum clenching force of a healthy adult, as well as a load of 135 N, corresponding to the bite force obtained within the 6 postoperative weeks according to previous studies. The bite force was applied perpendicularly to the occlusal surfaces of the first molar at the contralateral side of the fracture, which is more critical.
than if it were applied to the ipsilateral side. The proportions of the muscle (deep and superficial masseter, internal and external pterygoid, anterior and posterior temporal) reaction force magnitudes were defined according to previous studies. Mandibular movements were restricted at the condyles’ upper surface in all directions (Fig 1).

MATERIAL PROPERTIES

Distinct domains with varying patient-specific bone elastic properties were defined in the model by converting the voxel Hounsfield unit value in CT image to a certain bone density and Young’s modulus and assigning it to the corresponding volume. For the conversions, the equations for the femoral bone available in the literature were used. Young’s modulus values calculated from these equations were in the range experimentally found for the mandibular compact and spongy bone. The Poisson’s ratio was considered 0.3 for all elements of bone. The titanium hardware was considered linear, homogeneous, and isotropic. Properties of titanium alloy Ti-6Al-4V were assigned to all miniplates and screws ($E = 114$ GPa; $\nu = 0.34$).

FINITE ELEMENT MODEL

The commercial finite element software ABAQUS (Simulia, Dassault Systèmes) was used to simulate and analyze the mechanical problem. Based on an extensive sensitivity study on the mesh size and type, the second-order tetrahedral solid element C3D10 was preferred. At the bone, where the screws were located, at the screws themselves, as well as at the plate, where stress concentration is expected to occur, a dense mesh area was defined. For this area, the element size reduced up to 0.3 mm. The small mesh size contributed to accurately capturing the curvature along the screw’s surfaces. Using the adaptive mesh, coarse mesh areas were preferred toward the jaw’s anterior part and consequently to maintain the total elements number below 800,000 for computational efficiency.
This study assumed that the plates did not receive or transfer any force directly from the bone segments. Interaction between plates and screws and between titanium hardware and bone was considered fully bonded, using the tie constraint. Finally, the muscular loads were applied as surface traction.

**EVALUATION**

Both the magnitude and the direction of the developed displacements, along the condylar head fragment, were used to evaluate the plating designs’ performance. Displacements along the same direction for the proximal and distal fragments denoted a rigid fixation as both surfaces were moving more like a compact object.

Moreover, the stress and strain states were used to evaluate the osteosynthesis material (screws and plates) and the bone, respectively. According to recent studies, the maximum principal strain is a good indicator of the bone’s mechanical behavior when assessed using the finite element method. Von Mises stresses indicated areas where large displacements will outcome a potential yielding of the osteosynthesis material.

**Results**

**ANALYSIS OF DISPLACEMENT**

The displacement was analyzed for a load of a 135 N and 500 N, independently. A color scale showing the magnitude of the displacement for the fractured condylar process is shown in Figures 2 and 3, whereas the direction of the displacement vectors for the elements along the fracture line is reported in Figure 4.

The kappa plate produced the smallest displacement magnitudes in the proximal fragment and around the fracture and the trapezoidal plate the highest for both loading conditions. The remaining 2 plates produced similar magnitudes of displacement with the alpha plate showing a more homogenous distribution of the displacement field around the fracture. However, the magnitude of displacement for the various
plates for a 135 N loading was clinically not significant (Fig 2). On the other hand, when 500 N load was applied, the micromovement along the fracture line exceeded for the trapezoidal plate the critical limit of 0.15 mm, which could prevent bone healing. The micromovements for the rest 3 plates were below this critical limit (Fig 3).

The proximal and distal fragments showed the same direction of displacement for the elements around the fracture when the kappa and alpha plates were tested (Fig 4). On the other hand, when the rhomboidal and trapezoidal plates were examined, the 2 fragments showed a convergent movement near the fracture line. The parallel directions of displacement of the elements around the fracture for the kappa and alpha plates indicated a more rigid fixation because both fragments were moving as a compact object.

STRAIN IN BONE

Contours of maximum principal strains in the bone were collected for loads of 135 N and 500 N (Figs 5, 6). The critical yield tensile strain of human cortical bone, which can trigger bone resorption if an extended bone area is affected, is estimated at 0.4% according to relevant studies. For a 135 N load, a maximum principal strain above this limit was observed in limited areas around the screws for the trapezoidal and rhomboidal plates. When a 500 N load was applied, the principal strains in the bone around the screws exceed the critical value at all 4 plates. However, the affected area was smaller for the kappa and alpha plates and significantly more widespread for the rhomboidal and trapezoidal plates, extending in the bone around all 4 screws.

VON MISES STRESSES IN PLATES AND SCREWS

The results show that for all plates at a 135 N loading condition, the maximum von Mises stresses were well under the yield strength of titanium alloy (880 to 920 MPa), so all the plates were adequate for the fracture fixation for these loading conditions (Fig 7). For a 500 N applied load, the only plate showing stresses
closer to titanium’s yield stress was the rhomboidal plate (Fig 8). The maximal von Mises stresses were observed at the plate area corresponding to the fracture line and at the screws near and above the fracture line. The stresses were greater in the inner side of the fixation systems. Kappa and trapezoidal plates showed the lower von Mises stresses, followed by the alpha plate.

Discussion

Fractures of the condylar neck area represent 1 of the most challenging maxillofacial trauma categories because of the complex biomechanical behavior, the difficulty in accessing the area site of interest, and the constrictions regarding the size of the fragments. In addition to that, because of the narrow condylar neck, the course of the osteosynthesis lines is not that discrete as in the subcondylar area with implications to the biomechanics, the design of the plates, and the resulting rigidity of the fixation. Moreover, the lack of large-bone surfaces can make the fixation of these fractures challenging and contribute to additional instability when compared with subcondylar fractures.

In the present study, we compared 4 plate designs for the fixation of a condylar neck fracture using FEA. This noninvasive technique can accurately predict the mechanical behavior of long bones, although there are limitations for the mandible because of the complexity of the craniomandibular system. The anatomy and heterogeneity of the mandibular bone result in diverse biomechanical properties. For this reason, the mandible is a challenging field for the FEA.

Some fixation techniques applied in the subcondylar area, such as the 2 straight plates in the nonparallel configuration technique, considered biomechanically the gold standard, are often not applicable in the neck area. To solve this problem, many plate designs are available in the market, which makes the surgeon’s choice more difficult. FEA is a well-known technique widely used during the past years to assess, among others, several fixation techniques for fractures in
the mandible. Although FEA was performed for many fixation systems of lower condylar fractures, we are not aware of studies that assessed the complex biomechanical behavior of the condylar neck area by taking into consideration the difficulty of lack of broad and flat bone areas for the application of the plates. Moreover, the alpha-shaped and kappa-shaped plates, which were studied in this article and are specially designed for the condylar neck area’s narrow conditions, have not been simulated with FEA, to our knowledge.

In our present study, 4 different plate designs were used to fix a typical condylar neck fracture. Their performance regarding rigidity, stress in the plate and screws, and strain in the bone were evaluated. The loading conditions simulated the maximum chewing force for the first 6 weeks postoperatively (135 N) and the maximum clenching force of an adult (500 N).

According to our findings, for a load of 135 N, all 4 plates showed similar rigidity as the microdisplacements along the fracture line remained well below the critical limit, allowing bone healing. However, the rhomboidal and trapezoidal plates performed slightly worse than the other 2. Regarding the stresses in the metal parts, there were also no clinically significant differences regarding the stresses in the metal parts, which were all significantly below the yield strength of titanium. The strain in the bone exceeded the critical yield tensile strain of human cortical bone only in limited areas around only 1 screw when the trapezoidal and rhomboidal plates were used. Nevertheless, this could lead to bone resorption in these areas. These findings indicate that when a mild postoperative loading is applied, all 4 plates can offer adequate fixation of condylar neck fractures with a risk of delayed screw loosening only when the trapezoidal and rhomboidal plates are used.

When a loading force of 500 N was applied, the plates showed significant differences. An interesting correlation was found between the volume of the plate/number of screws and the rigidity of the fixation/strain distribution in the bone. The alpha and kappa plates (9 and 8 screws, respectively) performed better than the rhomboid and trapezoidal plates, which both have half of the volume of the first
ones and 5 and 4 screws, respectively, offering a more rigid fixation and a better distribution of the strains in the bone. The trapezoidal plate offered the less rigid fixation as the micromovements could lead to nonunion.

For the rhomboidal and trapezoidal plates, the strain in the bone exceeded the critical yield tensile strain of human cortical bone around all 4 screws. In contrast, for the alpha and kappa plates, this strain was only exceeded at 4 screws (out of 9 and 8 screws, respectively) and in more limited areas. This could trigger bone resorption and affect the fixation’s stability, especially for the 2 smaller plates where no additional screws can compensate for the potential loosening of the screws.

Meyer et al.\textsuperscript{2} studied the stresses in the mandible and proposed that a more rigid fixation can be achieved when the osteosynthesis is performed according to the compression and tension lines. Their findings recommended the trapezoidal plate as the best fixation technique for the subcondylar area.\textsuperscript{32,33} de Jesus et al.\textsuperscript{21} on the other hand, suggested that the smaller number of screws used for the trapezoidal plate in the subcondylar area causes higher tension concentrations in the bone around the screws and can lead to screw loosening, a finding that our study also confirms for the neck area. The existing literature is conflicting whether the increased number of screws impairs the bone integrity without any gain in the fixation rigidity or contributes to an increased fixation rigidity. These studies examined fixation techniques for fractures primarily in the subcondylar area\textsuperscript{9,21,34-37} and not in the condylar neck. For condylar neck fractures, in particular, there is some evidence in the literature that screw loosening can lead to fixation failure when trapezoidal plates are used.\textsuperscript{8,38}

Our simulations with different bite loadings suggest that more screws and bigger plates offer only slightly improved stability and no additional bone protection if the postoperative chewing force is kept low. On the contrary, if bigger functional loads are applied, the increased number of screws and the bigger plate

\begin{figure}
\centering
\includegraphics[width=\textwidth]{VonMisesStresses.png}
\caption{Von Mises stresses distribution in the fixating systems for a 135 N load. The red arrow indicates the area of the maximum stress concentration.}
\end{figure}
volume can significantly improve the rigidity and, more importantly, decrease the strains in the bone, which will prevent bone resorption and loosening of the screws.

In addition to the aforedescribed biomechanical behaviors, which can determine the selection of the fixation technique, there are inherent difficulties in the clinical practice in plating fractures of the condylar neck because of the size and spherical anatomy of the condylar head fragment. These difficulties were also apparent in our virtual model during the plates’ digital bending to match the anatomy of the condylar head fragment. The digital bending, in particular, of the plates with a wider upper area such as the trapezoidal plate, was more time consuming, and an additional effort had to be made to avoid collision between the screws in the condylar head fragment because of the considerable bending needed in order for the plates to match condylar head’s spherical anatomy. Despite the fewer limitations of the plates’ digital application compared with the clinical practice, this effort did not always lead to optimal placement of the screws in our virtual model (eg, the upper anterior screw of the trapezoid plate) because of the given small dimensions of the fragment. These disadvantages of the trapezoidal plate design, when applied to the condylar neck, may prevail over the benefits of the smaller size of the trapezoidal plate.

Taking into consideration the experimental conditions and inherent limitations of the present study, such as the proximity to the temporomandibular joint, the difficulties to precisely simulate the joint’s function and the insufficient data about the biomechanical properties of the mandibular bone, it can be concluded that the fixation of condylar neck fractures with all 4 plate designs can be adequate when the load is limited to 135 N, maybe with an increased risk of screw loosening for the rhomboidal and trapezoidal plates.

For an applied load of 500 N, the bigger plates with more screws (alpha and kappa plates) showed better rigidity of the fixation and strain distribution in the

FIGURE 8. Von Mises stresses distribution in the fixating systems for a 500 N load. The red arrow indicates the area of the maximum stress concentration.

bone. The trapezoidal plate produced the worst results and could lead to healing failure.

These findings implicate that the patient’s characteristics (expected postoperative functional loads, compliance, etc.) also play a role in the right technique selection.

The aforementioned findings need to be confirmed from further comparative and clinical studies.

References