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Numerical analysis of displacements of mandible bone parts using various elements for fixation of subcondylar fractures

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The paper presents an analysis of the distribution of dislocations in the case of fixation of a mandible low subcondylar fracture. Three types of elements have been used for fixation: NiTi shape-memory staples, miniaturized titanium plates and the Synthes compression plate, also called the Synthes zygomatic plate. The analysis was conducted using the finite element method. The degree of the mobility of the fractures was analysed as well as the tendency towards their separation on the basis of value analysis and the distribution of dislocation areas. The results obtained allowed a preliminary assessment of predicted healing effects and the possibility of being able to predict developing complications after osteosynthesis with the use of the elements analysed.

Key words: *mandible condylar process fracture, plate osteosynthesis, NiTi shape-memory staples, MES analysis*

1. Introduction

The most favourable treatment for the fractures of the mandible condylar process has long been the subject of research. Surgeons are trying to choose a method which allows patient to return quickly to their normal functioning and simultaneously is economically optimal. Plate osteosynthesis is currently the most popular method.

The medical market offers nowadays many plate systems, in which the stabilizing elements differ from each other in their shape and thickness. Due to the fact that the method which uses miniaturized plates is both popular and widely used, there are numerous academic publications in which biomechanical analyses of such a connection in the bone–implant arrangement were conducted. Numerical analyses, experimental research, and clinical observations above all showed that in the case of low subcondylar fracture the most beneficial treatment is a double fixation in the arrangement: a longer plate along the distal edge of the ramus and a shorter one in the mandibular notch area. Another way of fixation in this area is through the use of compression plates, which are especially designed for this area of the mandible. However, in clinical examinations a single compression plate is often used.

Prospecting for new methods for the fixation of condylar process fractures led to the use of NiTi shape-memory staples for the first time in the Department and Clinic of Craniomaxillofacial Surgery of the Medical University of Silesia in Katowice.

This paper aims to compare, through a biomechanical analysis, the distribution of dislocation areas for three types of fixation of the mandible condylar process. Miniaturized plates (a typical method used by craniomaxillofacial surgeons), the Synthes compression plate (favoured for exactly these fixations), and

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NiTi shape-memory staples (as a new treatment method for fractures in this area of the mandible) were used as the fixing elements.

The authors posed the question as to which type of implants is the most beneficial in the aspect of correct osteosynthesis and to which extent staples may replace plate methods in fixations of low subcondylar fractures. Behaviour and tendencies towards the separation of mandible bone fractures were evaluated based on the analysis of the area of dislocations which enabled the fixation to take place in optimal conditions.

2. Material and methods

Numerical analyses with finite elements were carried out and the results obtained were related to X-ray photographs and clinical observation.

Three cases of low subcondylar fracture fixations performed in the Craniomaxillofacial Surgery Clinic of the Medical University of Silesia were analysed:

Case One (figure 1a): a fixation with NiTi shape-memory staples, which are used in the Clinic in various size variants [3] with a span length from 15 mm, the length of the vertical legs equal to 5 mm and the leg angulation angle equal to 60°; the positioning of staples with respect to the fracture crack was set on the basis of preliminary numerical analyses carried out by the authors. In these analyses, the authors estimated the way of the staple positioning with respect to the favourable adhesion of bone fractures [4].

Case Two (figure 1b): a typical fixation with Martin's 5- and 4-hole titanium miniplates positioned according to the principles of correct osteosynthesis[5], [6].

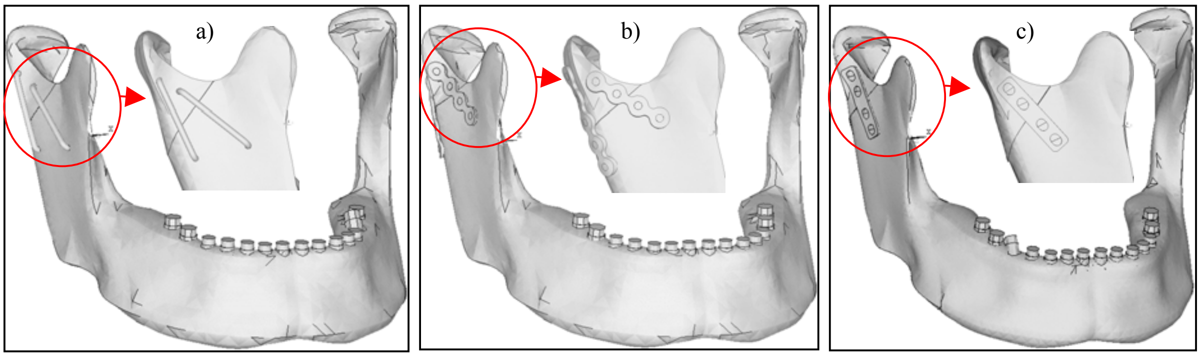

Fig. 1. Numerical models of fixations of low subcondylar process fractures

The numerical mandible model used in the examinations mapped the mandible anatomical structure, the activity of muscles, the way of load shifting and the mobility of the mandibular articulation [1]. Basic groups of muscles such as masseter, temporal muscle, medial pterygoid muscle and lateral pterygoid muscle were taken into account. The thickness of the model of callus between mandibular broken bone parts were taken for constant value of 0.1 mm.

Simulations of the changes in the mineralization of the callus were conducted from the initial state of healing to the bone adhesion period after about 6 to 8 weeks. The change of mineralization was simulated by a change of the elasticity modulus of a callus modelling element for the values of 2, 5, 10, 25, 50, 75, 100, 125, 150, 175 and 200 MPa. The value of callus modulus of elasticity was taken after KNETS [2]. It is obvious that the real value of Young's modulus of mineralized callus could be different.

Case Three (figure 1c): a fixation with the Synthes 4-hole, 2-mm thick titanium compression plate (preferred in this fracture area).

The load applied was equal to 100 N. The mandible load pattern took into consideration postsurgical recommendations relating to the possibility of food ingestion, and in consequence biting, that is a possible occurrence when applying a load to bone structures through the front teeth. One should consider spastical muscle contractions, which may cause great local loading.

3. Results

The results of the numerical analyses were presented as diagrams and dislocation distribution maps. The choice of the range of scale in the diagrams was

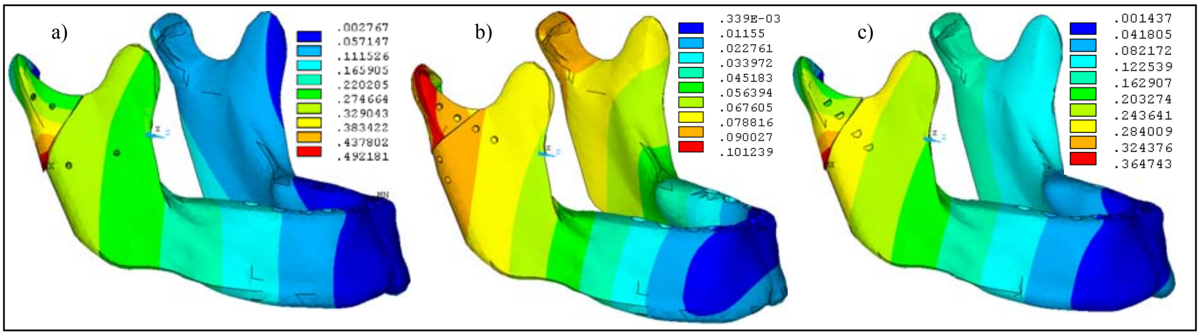

Fig. 2. Distribution of the U_{sum} (mm) displacements for fixations with:
a) NiTi staples, b) miniplates, c) a compression plate for the initial stage of medical treatment

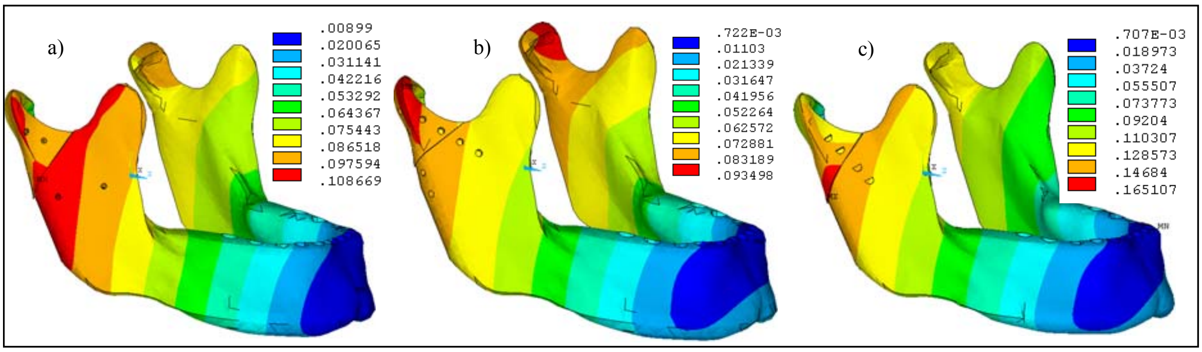

Fig. 3. Distribution of the U_{sum} (mm) displacements for fixations with:
a) NiTi staples, b) miniplates, c) a compression plate for the final stage of medical treatment

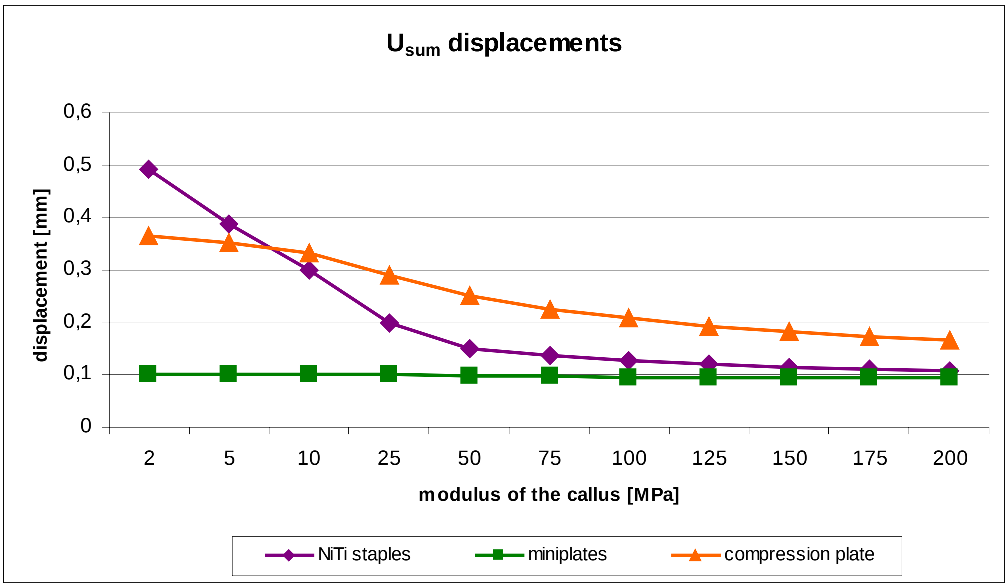

Fig. 4. Values of the U_{sum} (mm) displacements for the fixations
with a change in Young's modulus of the callus simulating element

made in such a way as to show most clearly the changes during the healing process.

During the initial stage, the general tendencies for a bone fragment to split were compared on the basis of the observation of the dislocation areas U_{sum} (mm) for the extreme values of Young's modulus of the callus, $E = 2$ MPa (the callus in the initial stage of the healing process) and $E = 200$ MPa (the callus mineralized in the final phase of adhesion) (figures 2 and 3).

In the fixation with miniaturized plates, the maximal values of U_{sum} and the distribution of these dislocations are indicative of the initial and final stages of the healing process. A large element of symmetry is noticed, which testifies to a good stabilization of bone fragments.

In the fracture fixation with the NiTi staples and with the compression plate, a similar tendency to medially dislocate a smaller bone fragment with its lower part may be observed in the initial stage of the healing process. The increase in the degree of callus mineralization causes a change in the dislocation distribution; for NiTi staple fixation this distribution is closer to the distribution observed with the miniplate fixation.

Figure 4 presents the changes of U_{sum} for all analyzed fixation types with a change in the callus mineralization degree. The change of the callus modulus has almost no influence on the U_{sum} value in the fixation with miniplates, whereas it significantly changes this value in other types of fixation. Despite the fact that during the initial stage of the healing process U_{sum} is greater for the NiTi staple stabilization, yet at the modulus value between 5 and 10 MPa this value is lesser than in an adaptation plate fixation, and at the value equal to 50 MPa, the value of U_{sum} gets closer to those observed for miniplates.

In the next stage, the mobility degree of bone fragments and the tendencies towards their splitting were evaluated. It was made through a dislocation area analysis along the individual axes of the estab-

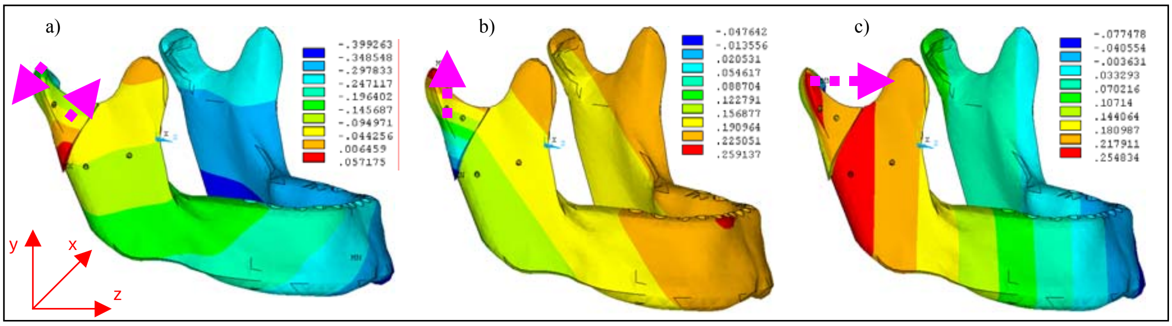

Fig. 5. Distributions of displacement components:
a) U_x, b) U_y, c) U_z for fixations with NiTi staples in the initial stage of medical treatment

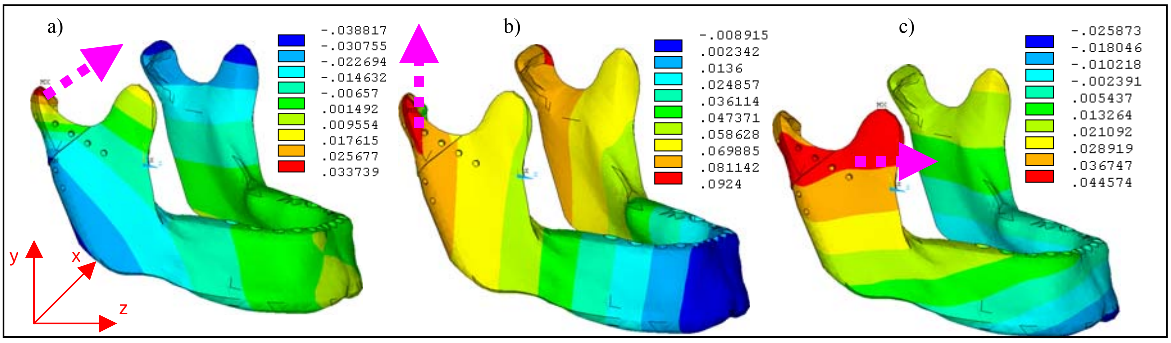

Fig. 6. Distributions of displacement components:
a) U_x, b) U_y, c) U_z for fixations with miniplates in the initial stage of medical treatment

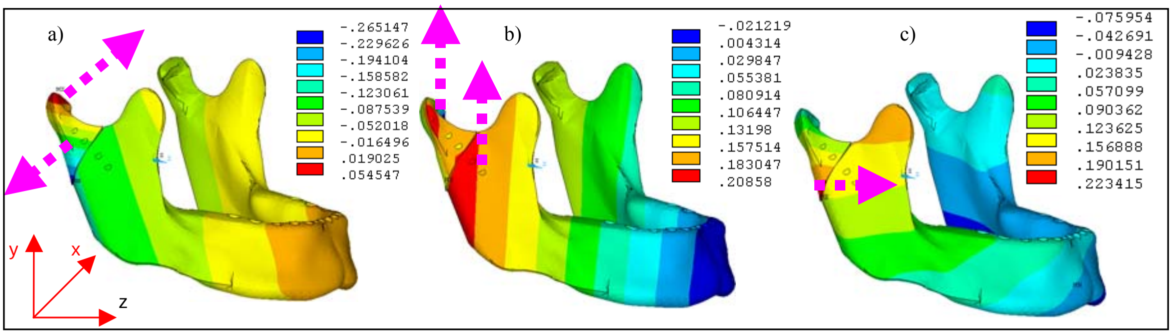

Fig. 7. Distributions of displacement components:
a) U_x, b) U_y, c) U_z for fixations with a compression plate in the initial stage of medical treatment

lished co-ordinate system for all kinds of fixation. Figures 5 to 7 show the maps of dislocation distribution U_x, U_y, U_z (mm) in the initial stage of the healing process, which occurs at the established value of the modulus of elasticity of the modelled callus E = 2 MPa.

In the fixations with NiTi shape-memory staples, it can be observed that a smaller bone fragment moves 0.26 mm upwards (figure 5b) and 0.25 mm to the front (figure 5c). The medial dislocation of its lower part is small (0.06 mm), but the upper part of the condylar process (the mandible head) moves 0.4 mm outwards (figure 5a). One may observe the rotation of the bone fragment: the upper part of the condylar process rotates inwards, and the lower part outwards, with a simultaneous pressing down of the bone fragments in the upper part of the fracture crack.

When a miniplate osteosynthesis is applied, very limited mobility of bone fragments can be observed. When observing the dislocation picture with respect to the y-coordinate axis (figure 6b), the symmetry for both mandibular ramii can be seen; this may prove that the stabilization of bone fragments is satisfactory. This is also verified in figure 6c showing the initial

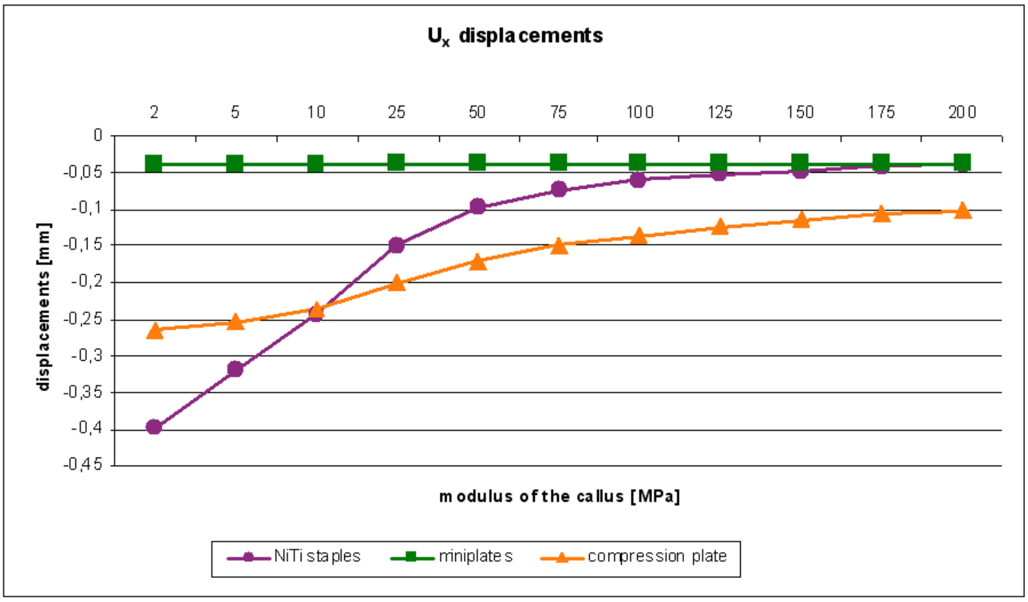

Fig. 8. Values of displacements along the x-coordinate axis for fixations with a change in Young's modulus of the callus simulating element

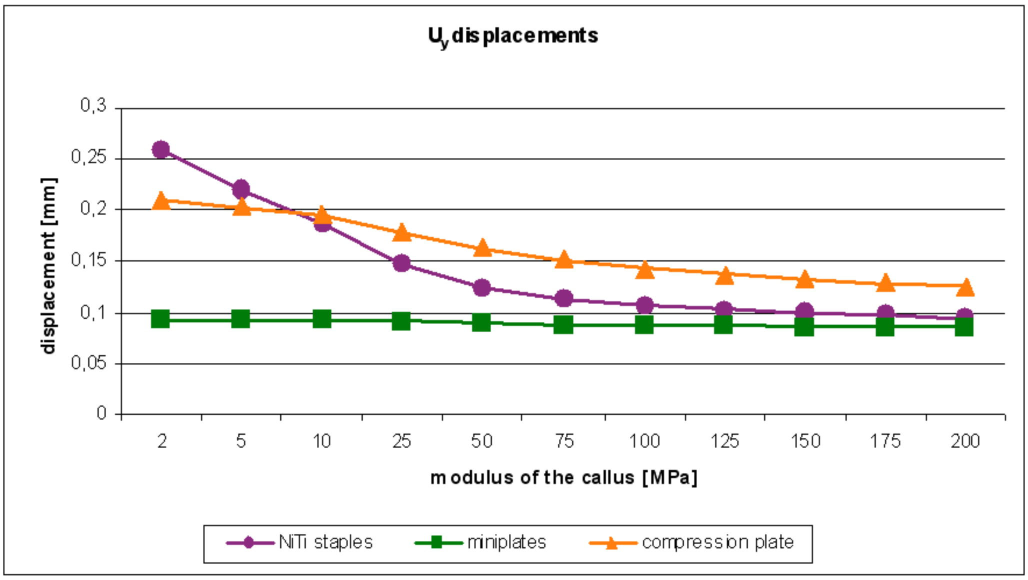

Fig. 9. Values of displacements along the y-coordinate axis for fixations with a change in Young's modulus of the callus simulating element

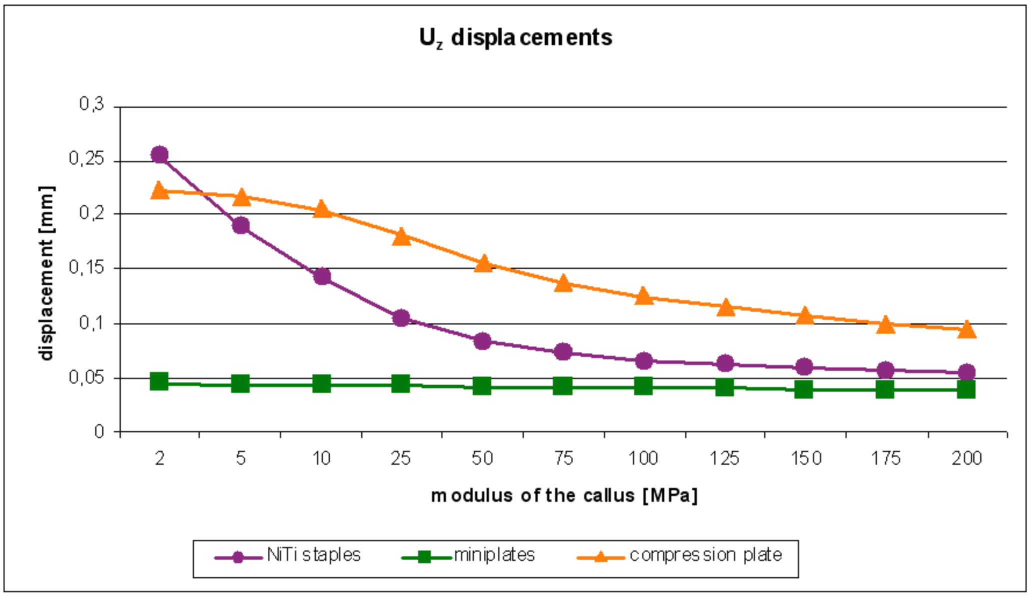

Fig. 10. Values of displacements along the *z*-coordinate axis for fixations with a change in Young's modulus of the callus simulating element

stage of the healing process, in which a forward dislocation (of 0.04 mm) of the area from the neck of the condylar process up to the coronoid process is seen. Small medially directed dislocations (0.03 mm) of the upper part of the condylar process (figure 6a) and 0.09 mm upward dislocations of the same part of the condylar process (figure 6b) may cause the minimal rotation of a smaller bone fragment in an inward direction.

For the case of the Synthes compression plate application as a fixing element, it can be seen that a longer bone fragment and the outer part of a shorter bone fragment move 0.2 mm upwards (figure 7b). The lower part of the shorter bone fragment moves also about 0.2 mm forwards (figure 7c). The shorter bone fragment moves in the lower part distinctly outwards (almost 0.27 mm), whereas in the upper part only 0.05 mm inwards (figure 7a). The separation of bone fragments in the fracture crack and a gentle rotation take place, which may cause problems with a proper adhesion.

The subsequent research stage was the analysis of the dislocation of mandible bone fragments for all cases of adhesion and for the changes in Young's modulus value of an element simulating the callus in a range from 2 MPa to 200 MPa. The results are shown in the form of diagrams in figures 8 to 10.

The maximal values of the U_x, U_y, U_z dislocations in the case of fixing miniplates almost do not change, but for the NiTi staples and the Synthes compression plate these changes are distinctly noticeable – they decrease largely, which means the reduction of the mobility of bone fragments along with an increase in the callus modulus, that is to say, with an increase in the degree of callus mineralization.

For the NiTi staples, one notices a rapid drop of the values in the initial stage of the bone healing process for all dislocation components. The value stabilizes at the adhesion degree, which complies with the value of the callus modulus E = 2 MPa, that is to say, in a relatively early stage of the healing process; the value is lesser than in the case of compression plate application. During the observation of the dislocation changes U_x, it can be noticed that NiTi staple fixation limits the mobility of bone fragments in the medial-side direction at the callus modulus value as low as E = 2 MPa, that is in a relatively early stage of the healing process.

The analysis of U_x dislocation showed that for both NiTi staples fixation and compression plate fixation greater dislocations in the lateral direction (outwards) appeared, although for the staples this refers to the lower part of the condylar process, and for the Synthes compression plate – to the upper part. In the case of miniplate fixation, the dislocation values are very low.

The observation of the changes of the U_y dislocations also demonstrated that for a miniplate osteosynthesis the mobility of bone fragments is minimal, but 10 times greater upwards than downwards. In NiTi staple and compression plate fixations, a greater tendency to dislocate bone fragment in an upward direction is clearly visible; and, for the staples, it is the upper part of the broken condylar process, and for the compression plate, additionally, the distal part of the bigger bone fragment.

The analysis of the U_z dislocations reveals that in the case where miniplates are used, mainly the upper, outer part of the condylar process dislocates, and the middle part and distal part of the ramus dislocate forwards. The same tendency and a similar dislocation are demonstrated by the lower part of the smaller bone fragment when the Synthes compression plate is used for fixation. For the staples the dislocation values are low and they take up the whole area of the condylar and coronoid processes.

4. Discussion and conclusions

Fixation with the use of a miniplate osteosynthesis enables one to obtain the minimal dislocation values (3 and 4 times lesser than for the other cases). However, too strong stabilization and a lack of favourable micromovements may (when the patient lacks their occlusal activity) result in a lack of adhesion, the creation of a false joint, and even local muscular atrophy. An increase in the degree of callus mineralization does not cause any significant changes in the dislocation values. This fact leads to the conclusion that miniplates connect bone fragments so strongly that an increase in the callus rigidity does not have any influence on the mobility of bone fragments.

In the NiTi staple and compression plate fixations of bone fragments, the greater mobility of a smaller bone fragment is visible. In the case of compression plate, there is a greater split of bone fragments and a gentle rotation of a smaller bone fragment, whereas with the NiTi staples a quicker rotation but lesser fracture crack split are noticed.

So far the issue of choosing an optimal treatment method for low condylar process fracture and the best fixation system has been unresolved. The use of a single-compression stabilizing plate for the osteosynthesis of low subcondylar fractures has become popular without any biomechanical examinations of fixation stability under in vitro conditions. Some authors describe failures in the stable osteosynthesis of the condylar process, such as the breaking of a plate or the losing of fastening screws, thus showing that a single miniplate may not be enough in this anatomical region [7]–[12].

TOMINAGA et al. [11] carried out a biomechanical evaluation of various methods of the open fixation of the bone fragments of low subcondylar fracture used today in oral and maxillofacial surgery. Skew and vertical subcondylar fractures were analyzed individually. The statistical analysis conducted by the above authors shows that not all the systems which stabilize bone fragments offer substantial resistance to the occlusal load. The greatest tolerance to load showed a fixation with two adaptation miniplates 2,0, both in fractures with a skew or vertical course of a fracture crack.

Similar results obtained WAGNER et al. [13], who conducted biomechanical tests in vitro with a mandible model based on finite elements in order to track the behaviour of the mandible condylar process fracture after fixation with the use of miniplates. These authors analyzed various kinds of fractures, various types of miniplates and various load conditions. They arrived at the conclusion that single plates of 1-mm and 1.5-mm thickness are insufficient for the osteosynthesis in this anatomical area. They recommend installing two plates, being 1.5 mm thick, in a combination with bicortical screws or one plate, being 2.0 mm thick. Similar research was conducted by KROMKA et al. [14], although they analysed low subcondylar fracture fixation with miniplates of various lengths and various ways of their setting.

HAUG et al. [15] in the in vitro research on synthetic polyurethane models of the mandible analyzed the biomechanics of four monocortical systems of plates used for the osteosynthesis of mandible condylar process fracture. In each case, only one plate was used. None of the systems examined proved to be perfect for this type of fracture, and 2.0-mm thick miniplates with a low dynamic pressing down showed statistically the best behaviour in mechanical tests.

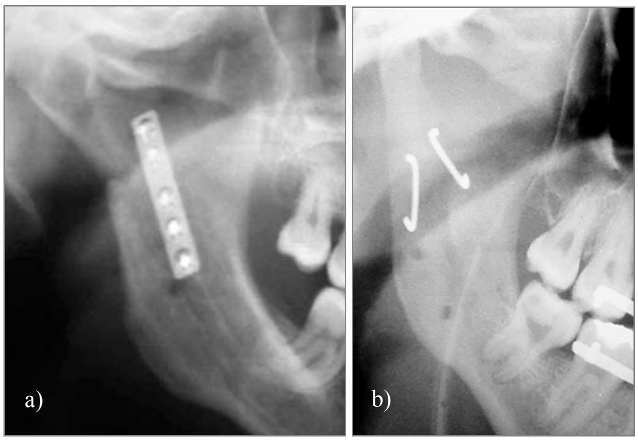

Fig. 11. X-ray showing complications in fixations with a single compression plate – secondary dislocation of bone fragments (a) and proper adhesion with NiTi shape-memory staples used for fixation (b)

Common financial problems in the health care system sometimes force surgeons to use materials sparingly, as is the case with the use of a single-plate fixation. This may result in developing complications such as a lack of adhesion, the breaking of an implant, or the rotating of a smaller bone fragment. The authors propose to solve this problem by applying NiTi shape-memory staples. When this happens, the postoperative rules of the fixation of bone fragments have to be correctly observed in the first days of medical treatment. This may be done, for instance, with inter-maxillary bonding, which seems to give better stabilizing effects and better prognosis (lack of complications) than those in the case of using a single plate (figure 11).

The analysis of the dislocation of the stabilized areas of condylar process fractures in the function of a callus mineralization degree, which is represented by the change in the callus elasticity modulus, illustrates the positive effects of osteointegration processes of the proposed fixation method with the use of the NiTi shape-memory staple. It is worth underlining that these numerical simulations become a preliminary study and that in the present stage they are not a basis for the decision of a final clinical method.

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