Evaluating the Effect of Minimizing Screws on Stabilization of Symphysis Mandibular Fracture by 3D Finite Element Analysis

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Abstract

Purpose The objective of this work is to integrate structural optimization and reliability concepts into mini-plate fixation strategy used in symphysis mandibular fractures. The structural reliability levels are next estimated when considering a single failure mode and multiple failure modes.

Patients and Methods A 3-dimensional finite element model is developed in order to evaluate the ability of reducing the negative effect due to the stabilization of the fracture. Topology optimization process is considered in the conceptual design stage to predict possible fixation layouts. In the detailed design stage, suitable mini-plates are selected taking into account the resulting topology and different anatomical considerations. Several muscle forces are considered in order to obtain realistic predictions. Since some muscles can be cut or harmed during the surgery and cannot operate at its maximum capacity, there is a strong motivation to introduce the loading uncertainties in order to obtain reliable designs. The structural reliability is carried out for a single failure mode and multiple failure modes.

Results The different results are validated with a clinical case of a male patient with symphysis fracture. In this case while use of the upper plate fixation with four holes, only two screws were applied to protect adjacent vital structure. This behavior does not affect the stability of the fracture.

Conclusion The proposed strategy to optimize bone plates leads to fewer complications and second surgeries, less patient discomfort, and shorter time of healing.

Keywords Structural optimization · 3D finite elements · Mandible fractures · Mini-plate fixation

Introduction

Fractures of the mandible are one of the most common facial injuries, because of its prominence, mobility and exposed position within the facial skeleton. These fractures most commonly occur in males as the result of motor vehicle crashes, falls, violence, and sports injuries [1]. The treatment option depend on open reduction and internal fixation using thinner miniplates to fixate the parts of fractures [2]. The primary goal of a bone plate should be to provide the maximum stability in the bone fracture region with a minimum amount of implanted material [2]. Achieving this goal will reduce patient complication, time in surgery, and overall patient discomfort [3].

Finite element (FE) analysis is a numerical analysis technique that can determine the displacement, stresses, and strains over an irregular solid body given the complex material behavior and the loading conditions imposed upon that body.

In a previous investigation related to mandible fracture [4], muscle forces have been ignored and only the bite force is applied, and the mandible (homogenous cortical bone) is fixed at its ends. For this loading case using the finite element method, Korkmaz [4] investigated several mini-plate systems and provided recommendations regarding mini-plate location, orientation, and type selection. In the present study, several muscle forces are considered (masseter, temporalis, lateral and medial pterygoid forces) in order to show the role of these forces [5].

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The objective of this work is to evaluate whether we have a suitable fixation with acceptable rigidity when minimizing screws fixation which allows the tow fragment fracture to be kept in good stability for rapid bone healing and limit any trauma to adjacent nerves. A 3-dimensional finite element model is used to formulate biomechanical justified positioning of the mini-plates to achieve good fixation. The topology optimization process is utilized in the conceptual design stage to predict the layouts of the existing mini-plate types. In this context, Lovald et al. [3] considered topology optimization of the mini-plate with the objective of minimizing its stiffness. The approach taken here is to minimize the maximum displacement at the fracture line.

Furthermore, in the classical deterministic design studies, we cannot completely guarantee a safe and satisfactory performance, due in part to the randomness of different bone properties, geometry and loading. Here, the different external forces are considered as uncertain parameters. A reliability algorithm is developed in order to assess the reliability level of the studied clinical case. The different resulting optimum solutions are validated when comparing with a clinical case of a male patient of 28 years of age which was carried out at Aleppo University Hospital by the second author.

Materials and Methods

The mandibular body was approximated as isotropic cortical bone. Fracture in the body region will exhibit a high degree of shearing and bending displacement under common loading forces (The fracture shows tension near the superior border and compression on its inferior border with a noticeable amount of shearing on occlusal plane). Traditionally, two plates are placed on the inferior and superior borders of the fracture [6]. A finite element model of human mandible was created for the purpose of designating and optimizing the effect of minimizing screws bone plate to fixate symphysis mandibular fracture.

Mechanical Properties

The mechanical properties of bone depend on composition and structure. It is well-known that the bone material structure is complex and shows an anisotropic mechanical response. For simplicity, the bone is here considered to be isotropic, homogeneous, and linearly elastic [7]. Its elastic behavior is characterized by the 2 material constants (Young's modulus E and Poisson's ratio ν). The most representative compositional variable is the ash density ρ_α with the following correlation [8].

$$E = 10500\rho_\alpha^{2.57\pm0.04} \quad (1)$$

$$\sigma_C = 117\rho_\alpha^{1.93\pm0.04} \quad (2)$$

where σ_C is the yield stress in compression. These expressions explain over 96 % of the statistical variation in the mechanical behaviour of combined vertebral and femoral data over the range of ash density ($\rho_\alpha = (0.03 \div 1.22 \text{ g/cm}^3)$). Eliminating ρ_α from (1) and (2) leads to:

$$\sigma_C = 117e^{\left(\frac{1.93\pm0.04}{2.57\pm0.04}\ln\left(\frac{E}{10500}\right)\right)} \quad (3)$$

Introducing the tension/compression ratio $R_{T/C}$, the yield stress in tension is obtained as:

$$\sigma_T = R_{T/C} \cdot \sigma_C \quad (4)$$

Different values have been used for the ratio $R_{T/C}$, ranging from 0.5 to 0.7 for cortical bone and from 0.7 to 1 for cancellous bone [9]. It is concluded that the yield stress in tension is always less than that in compression. Based on this observation the yield stress in tension will be used as a maximum allowable stress value in the mandible. Table 1 summarizes the used material properties [4]. However, to compute the yield stress for the used cortical bone ($E = 14000 \text{ MPa}$), Eq. 4 leads to $\sigma_T \approx 100 \text{ MPa}$ when considering the ratio $R_{T/C} = 0.69$ [10]. Equation 4 is then used to control the developed reliability algorithm.

Boundary Conditions

In this study, several different muscle forces are accounted in order to obtain realistic simulation models.

During the bite process, the digastric muscles are not very active and therefore not included in analysis [11]. In Fig. 1, an illustration of the twelve muscle forces (six on each side) applied to the mandible are shown. The values applied for each force are given in Table 2.

Topology Optimization

Topology optimization allows us to remove un-needed structural region. In Lovald et al. [3] the optimization problem was to minimize the structural compliance of the mini-plate subject to a required volume fraction. Unfortunately, this approach is a global indicator and does not guarantee that the displacements at the fracture zone are sufficiently small to allow for a fast healing process. In this work, the topology optimization problem is formulated to minimize the maximum displacement at the fracture line δ subject to a required mass reduction. The mathematical description is then:

$$\begin{aligned} \min : & \delta(x_i) \\ \text{s.t.} : & \frac{M(x_i)}{M_0} \leq f_M \\ \text{and} : & 0 \leq x_i \leq 1 \end{aligned} \quad (5)$$

Table 1 Material properties used in the studied finite element model

Material	Young's modulus (MPa)	Poisson's ratio	Density (Kg/m ³)	Yield stress (MPa)
Titanium	110,000	0.34	4500	860
Cortical bone	14,000	0.3	1000	100

Fig. 1 Boundary conditions**Table 2** Muscle forces [5]

Muscle forces	F_x [N]	F_y [N]	F_z [N]
Superficial masseter (SM)	18.2	303.3	12.1
Deep masseter (DM)	7.8	128.3	15.6
Anterior temporalis (AT)	−18.4	104.8	−43.8
Medial temporalis (MT)	−6.5	36.3	−53.1
Posterior temporalis (PT)	−3.4	6.8	−37
Medial pterygoid (MP)	187.4	325.1	−76.5

where $x_i \in [0, 1]$: are design variables representing internal pseudo-densities assigned to each finite element and f_M : is the ratio between current mass value $M(x_i)$ and initial one M_0 . Using formulation 5, the objective is to minimize the maximum displacement at the fracture surface in order to increase the stability level which is necessary for healing period reduction.

Reliability Analysis

In structural reliability theory many effective techniques have been developed during the last 40 years to estimate the reliability, namely FORM (First Order Reliability Methods), SORM (Second Order Reliability Method) and simulation techniques [12].

Fig. 2 Orthopantomogram of a male patient of age 28 years

Results

Problem Description (Clinical Case Study)

Figure 2 presents an orthopantomogram of a male patient at the age of 28 years. The surgical operation was carried out by the second author. There were no specific complications related to his treatment and the healing period was around 3 months. According to the clinical observations of Cox et al. [13], the upper limit of relative movement of the blocks of a broken mandible in the fracture section under a bite force should not exceed 150 μm which is defined as the limit value of sliding.

Numerical Simulation of Un-Fractured Mandible

In the studied model, due to the limited influence of the teeth on mechanical response of the mandible, these are ignored and removed in order to simplify the modeling. The mono-cortical screws were also modeled as simple cylinders of length appropriate for penetration. The von Mises stress values are considered as a fracture indicator [14]. This way the maximum values should not exceed the yield stress values in tension σ_T .

Two loading cases are considered: The first loading case (L1) is that the mandible is subjected to a bite force and all muscle forces are active and fixed at its extremities (Fig. 3a). The applied muscle forces: M^{Right} and M^{Left} denote the sum of masseter muscles (region B and C). T^{Right} and T^{Left} denote temporalis muscles (region D and E). P^{Right} and P^{Left} denote the sum of medial and lateral pterygoid muscles (regions F and G). The fixation is found in regions H and I. The bite force $F_b = 208(N)$, [15] is

Fig. 3 **a** Boundary conditions when considering muscles, loading case L1, **b** boundary conditions when ignoring muscles, loading case L2, **c** von Mises stress distribution when considering muscles and **d** von Mises stress distribution when ignoring muscles

applied in region A. The second loading case (L2) is that the mandible is subjected to only a bite force and fixed at its extremities [4]. The bite force is also located in region A and the fixation regions are in B and C (Fig. 3b). In Fig. 3, the red arrows indicate the different external forces in Table 3. The maximum von Mises stress is $\sigma_{\max} = 123.74$ MPa and it is obtained for the loading case where all muscles are ignored [4], i.e. loading case L2. However, the maximum von Mises stress is $\sigma_{\max} = 83.46$ MPa when considering all muscles being active, i.e. loading case L1. The von Mises stress distribution for the two loading cases are shown in Fig. 3c, d.

Table 3 Applied forces

Forces	Regions	F_x [N]	F_y [N]	F_z [N]
F^{Bite}	A	0	−208	0
M^{Right}	B	26	431.6	27.7
M^{Left}	C	−26	431.6	27.7
T^{Right}	D	−28.3	147.9	−133.9
T^{Left}	E	28.3	147.9	−133.9
p^{Right}	F	187.4	325.1	−76.5
p^{Left}	G	−187.4	325.1	−76.5

Topology Optimization of Fractured Mandible—Conceptual Design

The objective is to optimize the material distributions of the used mini-plates. In the previous work of Lovald et al. [3] the initial domain (design space) is taken as a plate with only 8 screws. However, in this work, a solid-like sheet with 12 screws is considered as an initial domain (Fig. 4a). This allows us to use several standard mini-plates (I, L, T and X).

Figure 4b shows the resulting topology, for $f_m = 0.3$, i.e. 30 % of material when taking into account muscle forces, i.e. loading case L1. Red color denotes material and blue color denotes no material. Comparing the resulting topology and the existing mini-plates, a possible layout is two I-plates with four holes in the line of osteosynthesis as indicated by principle of Champy and confirms that any supplemental holes will be not necessary [2, 6].

Validation of Mini-Plate Fixation—Detailed Design

From the obtained topology, a design consisting of two mini-plates of type I4 is considered. In order to get acceptable levels of rigidity and a limited displacement at the fracture line, double I mini-plates were fixed to the bone with six screws as shown in Fig. 5.

The lower I mini-plate is fixed by four screws whereas the upper plate was fixed by two screws. It is assumed that a perfect fit exists between plate hole and screw as well as the screws and hosting bone with no slippage at their interfaces [16]. Figure 5 shows the mini-plate fixation of the mandible after the fracture. The maximum von Mises stress is $\sigma_{\max} = 82.59$ MPa when considering all muscles.

Reliability Assessment of Detailed Design

During surgery, some muscles can be cut or harmed during the surgery operation, and it cannot be expected that all

muscles will operate at its maximum capacity. Therefore, there is a strong motivation to introduce the uncertainties. The muscle forces in Table 3 are taken as random variables which are supposed to be normally distributed. Their standard-deviations are assumed proportional to the mean values by 10 % [17]. The uncertainties due to the tolerance force measurements are considered. The upper and lower bounds are ± 20 % of the muscle force mean values. The resulting maximum stress values at the mean point are presented in Table 4. The given value of the bite force is: $F_b = 208(N)$. In this case the bite force and the most effective muscle force components are considered as random variables. The random variable vector contains 19 components: 1 for the bite force and 18 for the muscle forces.

Single Failure Mode (S.F.M.)

On the basis of Eq. (5), the reliability index of the structure is estimated. It can be concluded that the most critical constraint is the maximum stress at the left mandible part $H(u_i) = \sigma_{\max}^{Left} - \sigma_y^{Left} = 0$. The reliability index considering the force variability of the studied structure equals to: $\beta = 3.56$ that corresponds to probability of failure $P_f \approx 2 \times 10^{-4}$.

Multiple Failure Modes (M.F.M.)

The MPP is assumed to be located at the intersection of several constraint functions (limit states). For the random variables given in Table 4, the failure of the mini-plates will not take place. The only failure modes that will occur, is the mandible fracture. Thus, the considered limit states are: $H_1(u_i) = \sigma_{\max}^{Left} - \sigma_y^{Left} = 0$ and $H_2(u_i) = \sigma_{\max}^{Right} - \sigma_y^{Right} = 0$. The system reliability index is then $\beta = 5.10$, corresponding to the failure probability $P_f = 1.6 \times 10^{-7}$. According to Table 4, the maximum stress of the MPP in the right and left parts are found at the limitations with small tolerance.

Fig. 4 **a** 3D geometry model for both mandible parts and the used design domain for the mini-plate and **b** resulting topology for Eq. 5

Fig. 5 **a** Boundary conditions when considering all muscles, **b** von Mises stress distribution when considering all muscles

Table 4 Resulting response values

Parameters	Means	Design interval	MPP	
			S.F.M.	M.F.M.
$\sigma_{\max}^{\text{Upper}}$ (MPa)	33.15	$23.61 \leq \sigma_{\max}^{\text{Upper}} \leq 41.81$	30.15	29.48
$\sigma_{\max}^{\text{Lower}}$ (MPa)	31.49	$23.72 \leq \sigma_{\max}^{\text{Lower}} \leq 46.98$	27.74	29.15
$\sigma_{\max}^{\text{Right}}$ (MPa)	72.74	$59.41 \leq \sigma_{\max}^{\text{Right}} \leq 123.42$	88.25	98.57
$\sigma_{\max}^{\text{Left}}$ (MPa)	82.49	$67.16 \leq \sigma_{\max}^{\text{Left}} \leq 122.79$	99.87	99.98
β	–	$\beta \geq 3.56$	3.56	5.10
P_f	–	$P_f \leq 2 \times 10^{-4}$	2×10^{-4}	1.6×10^{-7}

Discussions

The resulting maximum stress ($\sigma_{\max} = 123.74$ MPa) when ignoring the muscle forces, exceeds the yield strength of the bone given in Table 1. However, the integration of different muscle forces leads to reasonable values ($\sigma_{\max} = 83.46$ MPa). Due to the uncertainty of the muscle forces, the objective was to introduce uncertainties in the muscle forces.

In the topology optimization procedure, the maximum displacement at the fracture line is minimized for a given mass. This choice is made to facilitate a high stability level which is necessary for reduction of the healing period. In the previous work of Lovald et al. [3] the rigidity of whole system was considered. Their approach is a global indicator and does not guarantee that the displacements at the fracture zone are sufficiently small to allow for a fast healing process.

According to Table 4, it is concluded that the selected fixation method (I4 + I2) is a promising solution. Here the maximum stress at the upper mini-plate ($\sigma_{\max}^{\text{Upper}} = 33.15$ MPa) is almost close to that of the lower mini-plate ($\sigma_{\max}^{\text{Lower}} = 31.49$ MPa). An increase of the number of screws

will have a marginal biomechanical effect for stabilizing the tow fragments. The results of this research confirm the need for two plates with 4 holes in the line of osteosynthesis as principle of Champy [2, 6] and it confirms that any supplemental holes will be not necessary. Also in the case of using the upper plate fixation with four holes, only two screws were applied to protect adjacent vital structure. This behavior will not affect the stability of the fracture.

Conclusion

The primary goal of fracture management is healing of the fractured bone resulting in restoration of form and function. Modern traumatology started with the development of osteosynthesis using mini-plates for the treatment of fractures. In this study, the correct position of mini-plates is confirmed in the symphysis or parasymphysis fracture respecting the ideal line for osteosynthesis presented by Champy. This result leads to the importance of fixation of symphysis or parasymphysis fracture by 2 I plates with 4 holes. When increasing the number of screws or holes the

biomechanical effects for stabilizing the two fragments is marginal. Since the maximum von Mises stress values of the upper and lower mini-plates are almost close, the solution optimality is demonstrated. Thus, the reduction of the number of screws used in the upper plates maintains the stability without any effects for increasing the tension in the region of fracture. This result helps the surgeon to give him the opportunity to reduce the number of screws without any consequence on the stability of fracture with the target to protect adjacent vital structure. The selected design is also considered as a reliable design with a reasonable probability of failure. The integration of reliability and optimization concepts into mini-plate fixation leads to both reliable and optimal designs. By using modern simulation design methods to optimize bone plates will lead to fewer complications and second surgeries, less patient discomfort, and shorter time of healing. The current study leads to a reasonable reliability level relative to the structural studies.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standards All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Human and Animal Rights Statement This article does not contain any studies with human participants performed by any of the authors but only using panoramic X-ray as a reference for the study.

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