

Finite element analysis of stress distribution on the mandible and condylar fracture osteosynthesis during various clenching tasks

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Abstract

Purpose The purpose of the study was to evaluate the effect of clenching tasks on the stress and strain of condylar osteosynthesis screws and plates, as well as on the stress, strain distribution and displacement on the whole mandible and bone surrounding screws.

Methods Three-dimensional finite element models of the mandible, two straight four-hole plates and eight screws were established. Six static clenching tasks were simulated in this study: incisal clench (INC), intercuspal position (ICP), right unilateral molar clench (RMOL), left unilateral molar clench (LMOL), right group function (RGF) and left group function (LGF).

Results Based on the simulation of the six clenching tasks, none of the inserted screws and plates were broken or bended. For the whole mandibular bone, the maximum von Mises stress and von Mises strain observed were yielded by the ICP. For the bone surrounding the inserted screws, the maximum von Mises stress and von Mises strain were yielded by the LMOL (49.2 MPa and 3795.1 μ).

Conclusion Clenching tasks had significant effects on the stress distribution on the condylar osteosynthesis and the bone surrounding screws. Contralateral occlusion task (LMOL) had the maximal results of von Mises stress and strain and healing problems could be occur, this result confirms the importance of soft diet after surgery.

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Introduction

Treating facial skeleton fractures is considered to be an important component of oral and maxillofacial surgical practice [1]. Essentially, this treatment has evolved from closed reduction to open reduction and internal fixation (ORIF) and widely accepted as *best practice* [1].

For those surgeons who choose to treat these fractures with ORIF, further discussion occurs concerning the number and pattern of plates that can be used [1]. The treatment of fractures in the condylar region should lead to as perfect as possible restoration of masticatory function [2].

The biomechanical functions of teeth generally result in stresses, which are transferred to mandible and condyles producing strains and stresses in all of them. Understanding the nature of strain and stress distribution is essential for better

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diagnosis and treatment of all maxillofacial diseases and restoration of masticatory function [3].

Unfortunately, the stresses cannot be measured directly in a non-destructive way. The number of direct studies on the masticatory system is limited, because of its difficulties [3].

During the latter decades, the finite element method (FEM) became a powerful analysis instrument of structural behaviour and interaction analysis of different bodies, systems and environments by using appropriate computational software [3].

In recent years, a number of research teams have used the finite element method to conduct biomechanical analysis on condylar base and neck fractures osteosynthesis. For example, Parascandolo et al. and Wagner et al. analysed the behaviour of single and double plates [5, 6]. Aquilina et al. and De Jesus et al. analysed three methods of condylar osteosynthesis [1, 7]. Kozakiewicz et al. presented an A-shape plate to fixate condylar base fracture [8]. However, these studies have merely used a single clenching task in their simulations except for Wagner et al. study which presented three clenching tasks. In other words, only one loading and boundary condition were selected in all studies mentioned before.

However, the effects of various clenching tasks on condylar osteosynthesis remain unclear. Therefore, in this study, we explored the effect of clenching tasks on condylar base osteosynthesis and surrounding bones.

The aims of this study were as follows:

1. To create a biomechanical three-dimensional model of mandible with condylar base fracture fixated with two four-hole straight plates placed in an angulated pattern stabilized with eight screws.
2. To analyse biomechanical behaviour of the osteosynthesis, mandible and bone surrounding the screws during several clenching tasks using finite element method.

Material and method

Construction of the models

Three-dimensional solid models of the human mandible were created from computed tomographic (CT) images (using *Mimics* software), two straight four-hole non-compression mini-plates and eight screws. The virtual plates and screws were used to simulate the osteosynthesis of the condylar fracture created on the right side of the mandibular model. The two plates were placed in an angulated pattern (Fig. 1b).

The plates were “virtually” bent, or *warped*, (using *Solid works* software) fitting the morphology of the condylar neck to simulate the clinical practice of bending the plates manually before internal fixation [1]. Plates were located *slightly off* the bony surface with no contact between the plates and bone (0.3-mm distance). This lack of contact was important for test of plates as a load bearing device [8]. The screw-to-plate and screw-to-bone interfacial conditions were assumed to be *bonded*.

In total, there were roughly 51,000 nodes (245,000 elements) in the whole model. The finite element analysis was performed using the ANSYS Workbench software v15 (ANSYS, Inc.).

Properties of material

The models were considered to be a *non-homogeneous* with eight different material properties (Table 1), *isotropic*, and linear elastic. Properties were assigned on the basis of CT density (*Hounsfield units HU*) as in previously published protocols [9] (Fig. 2). The Young’s module (E) and the Poisson ratio (ν) were 115,000 MPa and 0.34 for plates and screws [7].

Muscular forces and constraints

The loading conditions pertained to seven principal muscles: the superficial masseter (SM), deep masseter (DM), medial pterygoid (MP), inferior lateral pterygoid (ILP), anterior

Fig. 1 Finite element model of the mandible and condylar osteosynthesis: **a** Whole model, **b** closed view

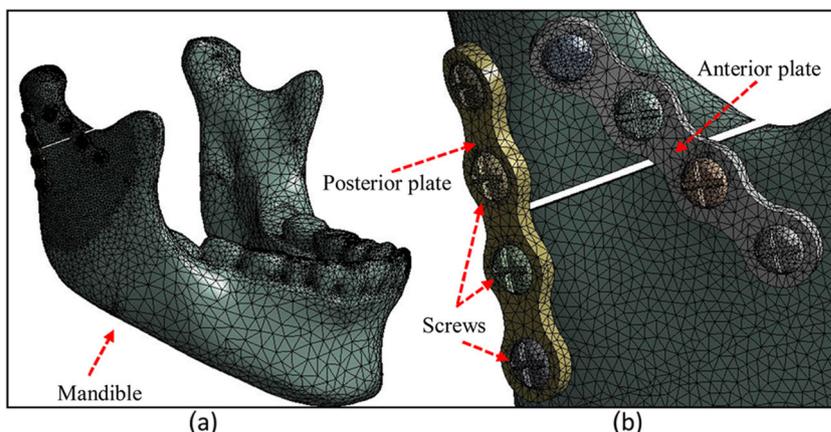


Table 1 Allocation of material properties to elements in the finite element model according to the distribution of (HUs) on (CT) [1]

Material properties of elements	Young’s modulus (MPa)	Density (T/mm3)
MAT 1	1572.0	2.508e-10
MAT 2	1868.6	2.916e-10
MAT 3	2223.4	3.325e-10
MAT 4	10,786.8	1.094e-09
MAT 5	21,734.2	1.855e-09
MAT 6	27,082.2	2.190e-09
MAT 7	32,704.3	2.525e-09
MAT 8	38,575.4	2.860e-09

temporalis (AT), middle temporalis (MT), and posterior temporalis (PT) (Fig. 3).

Six static clenching tasks were simulated in this study: incisal clench (INC), intercuspal position (ICP), right unilateral molar clench (RMOL), left unilateral molar clench (LMOL), right group function (RGF), and left group function (LGF). The magnitude and directions of the seven muscular forces and constraint region are listed in Table 2. All raw data for the

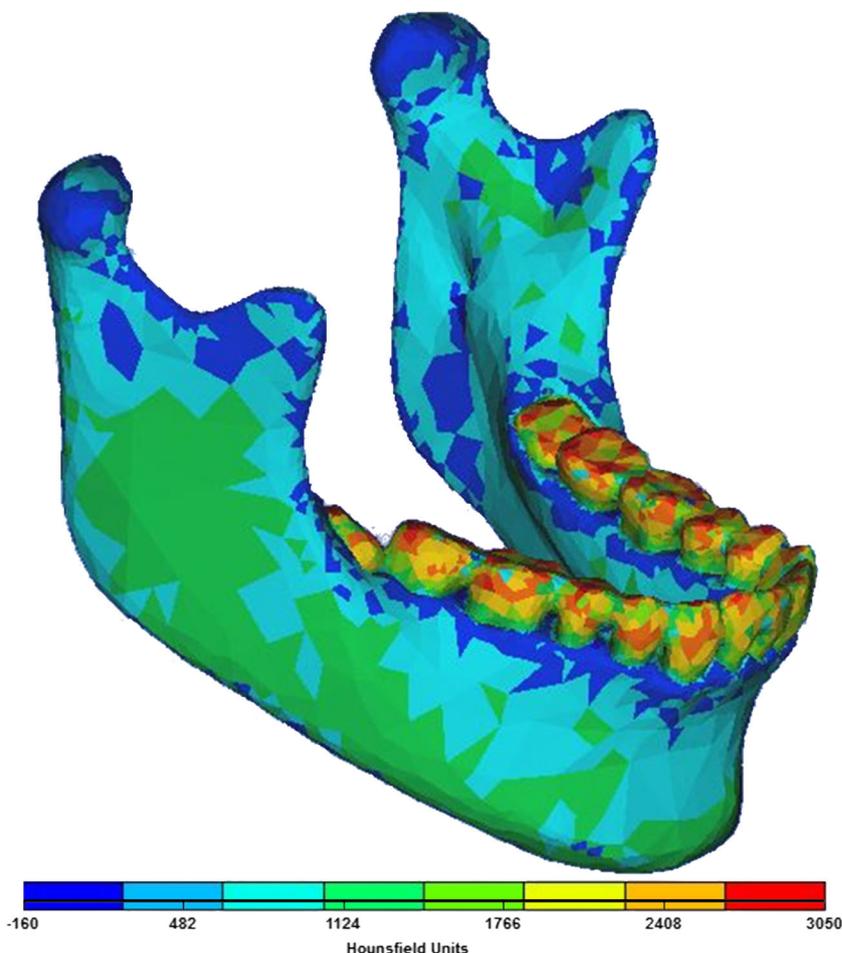
loading conditions were obtained from a study by Koriotoh and Hannam (1994) [4].

Analysis of results

The models were evaluated using a ratio in MPa (N/mm²). The tension fields over bone and osteosynthesis were evaluated using von Mises analysis (maximum stress level). A colour scale with von Mises stress and strain values (varying in MPa and μm) was used and each colour map presented a specific scale according to the result under study (Fig. 4).

After solving each model, the relative movement between the proximal and distal fragments was calculated. Von Mises (VM) stresses and strains were also recorded for each clenching task mandible, plates, anterior and posterior screws and bone surrounding screws. The top 0.1 % of the stressed bricks was not considered in the analysis, as they were likely to indicate stress artefacts in the model [1]. Using Microsoft Excel (version 2013), maximum values were obtained from the data for the remaining “brick” elements. Care was taken not to consider stresses

Fig. 2 The model after assigning material properties as eight groups relating to (HU). Areas in the model that are shown in red (e.g. cusp tips of the teeth) are those with the highest radiodensity (3000 HU). Areas in the model that are shown in dark blue are those with the lowest radiodensity (≤ 0 HU)



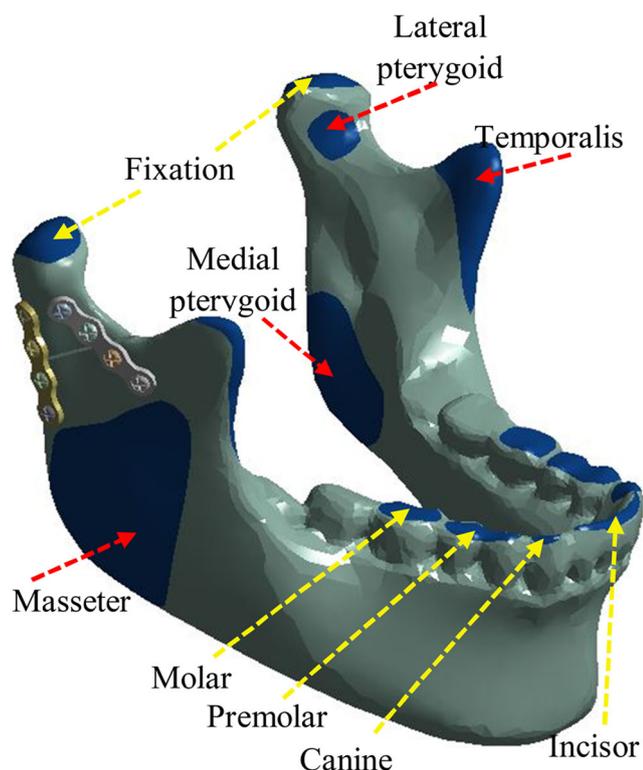


Fig. 3 Muscular force (red arrow) and constraints (yellow arrow) applied in finite element simulation

in elements close to the stiff link connections, as these links can cause highly localized regions of artificially high strain [1].

To compare stresses around the screw-holes in different clenching tasks, bricks were selected and grouped around the screw-holes using multiple cylindrical coordinate systems based on the shaft of the screws [1] (Fig. 5). Data about VM were then extracted from the grouped bricks and compared.

Results

In this study, the following evaluation parameters were used: six clenching tasks, the von Mises stress, the von Mises strain and the relative micro-motion between the fracture fragments. Graphics were used to visualize the INC simulation results, which comprised the relative micro-motion between the fracture fragments, the von Mises strain and von Mises stress on the whole bone (Fig. 4). Figure 6 shows the von Mises strain on the bone surrounding the screws, the von Mises stress of the screws and the von Mises stress of the plates. Table 3 shows the analysis results of the six clenching tasks, von Mises stress of screws and plates, micro-motion between the fragments, and von Mises stress and strain on the mandible and bone surrounding screws.

Von Mises stress of plates and screws

A mechanical analysis of the plates demonstrated that the values of von Mises stress on the anterior plate for each of the six clenching tasks were all less than von Mises stress on the posterior plate (less than 220 MPa). The maximum value for the LMOL (215.36 MPa) was approximately 5.8 times greater than the minimum value for the RGF (37.369 MPa) on posterior plate.

Furthermore, the maximum von Mises stress on the screws for each of the six clenching tasks ranged between 25.825 MPa (RGF, anterior screws) and 224.34 MPa (LMOL, posterior screws). The von Mises stresses on the anterior screws in the six clenching tasks were all less than that on the posterior screws.

Von Mises stress and strain of the whole bone

A whole mandible bone mechanical analysis indicated that the maximum and minimum von Mises stress and strain occurred at the ICP (45.874 MPa and 3860.8 μ) and the RGF (15.318 MPa and 1342.1 μ).

Von Mises stress and strain of bone surrounding screws

The mechanical analysis of the bone surrounding screws showed the following von Mises stress and strain values regardless of the clenching tasks involved. The bone surrounding screws exhibited a von Mises stress of less than 49.153 MPa (LMOL, posterior screw) but greater than 6.769 MPa (RGF, anterior screws) and yielded a von Mises strain less than 3795.1 μ (LMOL, posterior screw) but greater than 1327 μ (RGF, anterior screws).

Relative micro-motion between the fracture fragments

The analysis results revealed that the maximum relative value of micro-motion was for the LMOL (160.06 μ m) which is approximately 5.3 times greater than that for the RGF value (30.335 μ m).

Discussion

The incidence of condylar fractures has reached in the recent time 27 % of mandibular fractures [10]. For fractures treated by (ORIF), many fixation methods could be used. It is evident that the use of two plates correctly positioned (angulated) represents the best solution to obtain a stable osteosynthesis [5] and considered as an ideal treatment for mandibular condylar fracture [11].

Mandibular movements are controlled by the various muscles attached to the mandible, which contract to perform upward, downward, forward, backward, leftward, and rightward movements [12]. Koriath and Hannam (1994) reported that various clenching tasks are performed by 9 mandibular muscles

Table 2 Muscular force and constraints of the six clenching tasks

Clenching tasks	Side	Direction	Muscular force (N)							Constraint ^a
			SM	DM	MP	AT	MT	PT	ILP	
INC	Right	Force	76.2	21.2	136.4	12.6	5.7	3.0	47.5	Constrained the incisor regions
		Fx	-15.8	-11.6	66.3	-1.9	-1.3	-0.6	29.9	
		Fy	67.3	16.1	107.8	12.5	4.8	1.4	-8.3	
	Fz	31.9	-7.6	50.9	0.6	-2.9	-2.6	36.0		
	Left	Force	76.2	21.2	136.4	12.6	5.7	3.0	47.5	
		Fx	15.8	11.6	-66.3	1.9	1.3	0.6	-29.9	
Fy		67.3	16.1	107.8	12.5	4.8	1.4	-8.3		
ICP	Right	Force	190.4	81.6	132.9	154.9	91.8	71.0	18.1	Constrained the canine and premolar regions
		Fx	-39.4	-44.6	64.6	-23.1	-20.4	-14.8	11.4	
		Fy	168.3	61.9	105.1	153.0	76.8	33.7	-3.1	
	Fz	79.8	-29.2	49.6	6.8	-45.9	-60.8	13.7		
	Left	Force	190.4	81.6	132.9	154.9	91.8	71.0	18.1	
		Fx	39.4	44.6	-64.6	23.1	20.4	14.8	-11.4	
Fy		168.3	61.9	105.1	153.0	76.8	33.7	-3.1		
RMOL	Right	Force	137.1	58.8	146.9	115.4	63.1	44.6	20.1	Constrained the right molars
		Fx	-28.4	-32.1	71.4	-17.2	-14.0	-9.3	12.6	
		Fy	121.2	44.5	116.1	114.0	52.8	21.1	-3.5	
	Fz	57.4	-21.0	54.8	5.1	-31.5	-38.1	15.2		
	Left	Force	114.2	49.0	104.9	91.7	64.0	29.5	43.5	
		Fx	23.6	26.7	-51.0	13.7	14.2	6.1	-27.4	
Fy		101.0	37.1	83.0	90.5	53.6	14.0	-7.6		
LMOL	Right	Force	114.2	49.0	104.9	91.7	64.0	29.5	43.5	Constrained the left molars
		Fx	-23.6	-26.7	51.0	-13.7	-14.2	-6.1	27.4	
		Fy	101.0	37.1	83.0	90.5	53.6	14.0	-7.6	
	Fz	47.9	-17.5	39.1	4.0	-32.0	-25.2	32.9		
	Left	Force	137.1	58.8	146.9	115.4	63.1	44.6	20.1	
		Fx	28.4	32.1	-71.4	17.2	14.0	9.3	-12.6	
Fy		121.2	44.5	116.1	114.0	52.8	21.1	-3.5		
RGF	Right	Force	34.3	29.4	12.2	104.3	61.2	46.8	39.5	Constrained the right canine, premolars, and molars
		Fx	-7.1	-16.0	5.9	-15.5	-13.6	-9.7	24.9	
		Fy	45.4	16.1	105.1	10.9	4.8	2.2	-1.6	
	Fz	21.5	-7.6	49.6	0.5	-2.9	-3.9	7.1		
	Left	Force	51.4	21.2	132.9	11.1	5.7	4.5	9.4	
		Fx	10.6	11.6	-64.6	1.6	1.3	0.9	-5.9	
Fy		45.4	16.1	105.1	10.9	4.8	2.2	-1.6		
LGF	Right	Force	51.4	21.2	132.9	11.1	5.7	4.5	9.4	Constrained the left canine, premolars, and molars
		Fx	-10.6	-11.6	64.6	-1.6	-1.3	-0.9	5.9	
		Fy	45.4	16.1	105.1	10.9	4.8	2.2	-1.6	
	Fz	21.5	-7.6	49.6	0.5	-2.9	-3.9	7.1		
	Left	Force	34.3	29.4	12.2	104.3	61.2	46.8	39.5	
		Fx	7.1	16.0	-5.9	15.5	13.6	9.7	-24.9	
Fy		45.4	16.1	105.1	10.9	4.8	2.2	-1.6		
Fz	21.5	-7.6	49.6	0.5	-2.9	-3.9	7.1			

All raw data were obtained from Koriotoh and Hannam [4]

Muscular forces: *SM* superficial masseter, *DM* deep masseter, *MP* medial pterygoid, *ILP* inferior lateral pterygoid, *AT* anterior temporalis, *MT* middle temporalis, *PT* posterior temporalis. Clenching tasks: *INC* incisal clench, *ICP* intercuspal position, *RMOL* right unilateral molar clench, *LMOL* left unilateral molar clench, *RGF* right group function, *LGF* left group function

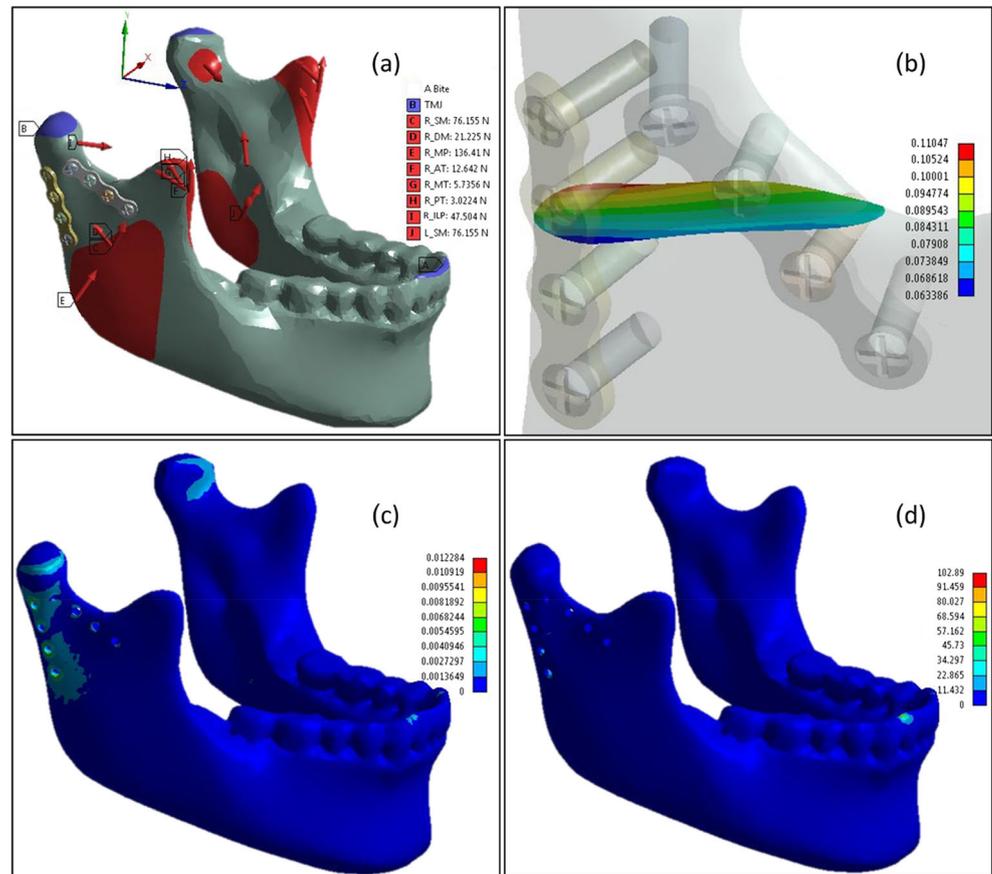
^a The models were constrained in all directions at the nodes on the top of the condyle in all clenching tasks

[4]. Effects of clenching site have admitted on condyle fracture region [6]. Still this mechanism is not obvious enough.

Finite element simulations are a common tool used for biomechanical analysis, which can obtain parameters not easily measured in in vitro experiments, such as the internal stress

and strain of bones and osteosynthesis [12]. FEM recently used to investigate distribution forces among osteosynthesis and bone [1, 5, 9]. Thus, we used the FEM to analyse the effects of clenching tasks on the biomechanical behaviours of condylar base fracture osteosynthesis and surrounding bones.

Fig. 4 Finite element simulation of the INC model: **a** constraint and INC, **b** relative micro-motion between the fracture fragments (mm), **c** von Mises strain of the whole mandible, **d** von Mises stress of the whole mandible (MPa)



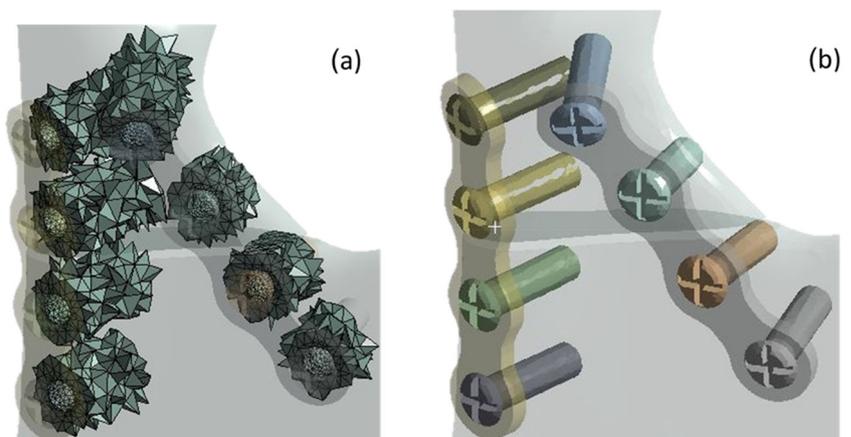
In studies regarding the finite element simulation of mandible movements and clenching tasks, authors have assigned nine [13], seven [14], five [2], four [1, 3], three [6] and two mandibular muscles [15] in their loading condition settings. Also previous FE studies on condyle fracture osteosynthesis were deferent in simulating bite forces either biting on contralateral molar [1, 9], ipsilateral side [7], or anterior teeth [8], or comparing three tasks [6].

Clenching tasks in the study model were simulated involving seven mandibular muscles—same used by Lovald et al. [14]—to investigate strain distribution. This model is considerably

larger and more complex than previous human mandible models which reported as being homogeneous [4–8, 11, 12, 14].

When performing the LMOL, the maximum von Mises stress in the plates and screws were (215.36 and 224.34 MPa, respectively) on the posterior osteosynthesis, which is less than a quarter of yield stress (934 MPa) [8] and a half of fatigue limit for the bending of titanium alloy (450 to 500 MPa) [6]. Therefore, the fracture or *bending* of the condylar *osteosynthesis* was *unlikely* in all clenching tasks in this study; this emphasized the validation of two oriented plates' method in treating condylar base fracture.

Fig. 5 Solid model: **a** closed view of bone surrounding the screws, **b** closed view of condyle osteosynthesis



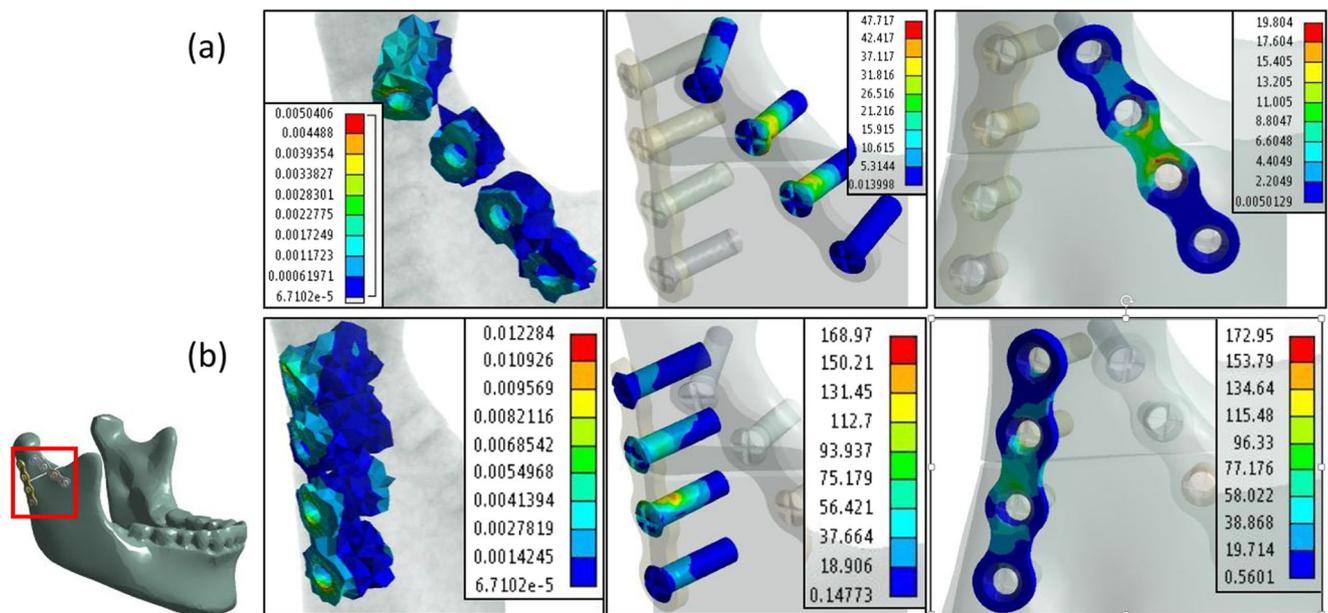


Fig. 6 Finite element simulation of the INC model: von Mises strain of the surrounding bone (*left*), von Mises stress of screws (*middle*) and von Mises stress of plate (*right*). From top to bottom: **a** anterior osteosynthesis region, **b** posterior osteosynthesis region. The *bottom-left image* shows the view orientation and region

Similar finding was found by Wagner et al. that the maximum values appeared in contralateral occlusion clenching task (LMOL) on the posterior plate. But their simulation results differed from those in this study—maximum von Mises stress was approximately 440 MPa in Wagner’s study—because of differences in the loading conditions—only three masticatory muscles were simulated in Wagner et al. study—as well as in the geometry and material assignment.

Concerning the von Mises stress and strain generated by the six clenching tasks in the whole mandible, the results were as follows (after ignoring the values in elements close to the stiff link connections): ICP yielded a maximum von Mises strain (3860.8 μ); RGF yielded a minimum von Mises strain (1342.1 μ). Previous study indicated that when the von Mises strain of the bone exceeds 4000 μ , pathologic overload may

Table 3 Simulation results for the six clenching tasks

Component	Evaluation parameter (maximum value)	Unit	Clenching tasks					
			INC	ICP	RMOL	LMOL	RGF	LGF
Anterior screws	Von-Mises stress	MPa	47.717	84.782	52.631	103.11	25.825	46.121
Anterior plate	Von-Mises stress	MPa	19.804	32.524	20.937	37.938	10.776	20.107
Posterior screws	Von-Mises stress	MPa	168.97	201.14	147.64	224.34	30.109	185.16
Posterior plate	Von-Mises stress	MPa	172.95	179.67	136.18	215.36	37.369	174.89
Fracture surface	Relative micro-motion	μm	110.47	147.57	97.314	160.06	30.335	107.52
Mandible	Von-Mises stress ^a	MPa	28.900	45.874	25.090	37.932	15.318	24.160
	Von-Mises strain ^a	μ	2056.3	3860.8	2537.5	3486.9	1342.1	1872.9
Bone surrounding anterior screws	Von-Mises stress ^a	MPa	11.477	21.265	13.121	23.057	6.769	10.105
	Von-Mises strain ^a	μ	1888.7	3449.9	2100.5	3875.3	1327.0	1720.4
Bone surrounding posterior screws	Von-Mises stress ^a	MPa	31.370	45.911	31.141	49.153	8.533	29.145
	Von-Mises strain ^a	μ	2283.8	3586.2	2372.2	3795.1	684.3	2078.4

INC incisal clench, ICP intercuspal position, RMOL right unilateral molar clench, LMOL left unilateral molar clench, RGF right group function, LGF left group function

^a Values in elements close to the stiff link connections were ignored

occur, leading to *bone resorption* [16], so that *will not occur* in this study.

Von Mises stress was proposed as an indicator in the assessment of bone remodelling; Sugiura et al. indicated that when stress in bone exceeds 50 MPa, this leads to bone resorption [17]. In our simulations, the maximum von Mises stress did not exceed 50 MPa. Therefore, in this study, the using of two plates was unlikely to cause bone resorption in the mandible.

For relative micro-motion, the maximum value resulted in LMOL clenching task (160.06 μm), this value exceeded marker value (150 μm) which was assumed to be a marker for increasing risk of clinical problems with healing of the fracture [18]. This outcome expresses that biting on contralateral side could have high risk of healing problems. Therefore, care should be taken to confirm soft diet after surgery.

As with any simulation approach, our study encountered a few limitations: first, ignoring regions of artificially high strains. Although these regions were occurred in finite element simulations [1], care must be taken in future simulations to deal with such errors. Second, only two plates' method was used in this simulations; analysis of other methods has yet to be performed. And further work is needed to validate these results against experimental data.

Conclusion

In this study, we performed simulations and analysed the effects of six clenching tasks on the biomechanical behaviours of condylar base fracture osteosynthesis and surrounding bone. Our observations are as follows:

- (1) The clenching tasks significantly influenced the von Mises stress and strain of the whole bone.
- (2) Healing problems could occur with contralateral biting; this result confirms the importance of soft diet after surgery.
- (3) The studied fixation method could withstand all occlusal conditions without fail (fracturing, bending or bone resorption).
- (4) Contralateral occlusion clenching task could be the suitable biting simulation for future FE studies on condyle fracture because of the maximal results of von Mises stress and strain.

References

1. Aquilina P, Chamoli U, Parr WC, Clausen PD, Wroe S (2013) Finite element analysis of three patterns of internal fixation of fractures of the mandibular condyle. *Br J Oral Maxillofac Surg* 51(4): 326–331. doi:10.1016/j.bjoms.2012.08.007

2. Kleinheinz J, Meyer C (2009) Fractures of the mandibular condyle: basic considerations and treatment. In: Meyer C (ed) *Biomechanics*. IBRA/Quintessence, London, p 147
3. Pileicikiene G, Surna A, Barauskas R, Surna R, Basevicius A (2007) Finite element analysis of stresses in the maxillary and mandibular dental arches and TMJ articular discs during clenching into maximum intercuspation, anterior and unilateral posterior occlusion. *Stomatologija/issued by public institution "Odontologijos studija"* [et al] 9(4):121–128
4. Korioto TW, Hannam AG (1994) Mandibular forces during simulated tooth clenching. *J Orofac Pain* 8(2):178–189
5. Parascandolo S, Spinzia A, Parascandolo S, Piombino P, Califano L (2010) Two load sharing plates fixation in mandibular condylar fractures: biomechanical basis. *J Craniomaxillofac Surg: Off Publ Eur Assoc Craniomaxillofac Surg* 38(5):385–390. doi:10.1016/j.jcms.2009.10.014
6. Wagner A, Krach W, Schicho K, Undt G, Ploder O, Ewers R (2002) A 3-dimensional finite-element analysis investigating the biomechanical behavior of the mandible and plate osteosynthesis in cases of fractures of the condylar process. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 94(6): 678–686. doi:10.1067/moe.2002.126451
7. de Jesus GP, Vaz LG, Gabrielli MF, Passeri LA, Oliveira TV, Noritomi PY, Jurgens P (2014) Finite element evaluation of three methods of stable fixation of condyle base fractures. *Int J Oral Maxillofac Surg* 43(10):1251–1256. doi:10.1016/j.ijom.2014.07.011
8. Kozakiewicz M, Swiniarski J (2014) "A" shape plate for open rigid internal fixation of mandible condyle neck fracture. *J Craniomaxillofac Surg: Off Publ Eur Assoc Craniomaxillofac Surg* 42(6):730–737. doi:10.1016/j.jcms.2013.11.003
9. Aquilina P, Parr WC, Chamoli U, Wroe S (2015) Finite element analysis of patient-specific condyle fracture plates: a preliminary study. *Craniomaxillofac Trauma Reconstr* 8(2):111–116. doi:10.1055/s-0034-1395385
10. Rashid A, Eyeson J, Haider D, van Gijn D, Fan K (2013) Incidence and patterns of mandibular fractures during a 5-year period in a London teaching hospital. *Br J Oral Maxillofac Surg* 51(8):794–798. doi:10.1016/j.bjoms.2013.04.007
11. Haowei X, Jun H, Wenyu Y, Jinli L, Yukun H, Ming S (2014) Application and effective evaluation of rigid internal fixation with double plates in condylar fracture. *West China journal of stomatology* 32:575–577
12. Huang HL, Su KC, Fuh LJ, Chen MY, Wu J, Tsai MT, Hsu JT (2015) Biomechanical analysis of a temporomandibular joint condylar prosthesis during various clenching tasks. *J Craniomaxillofac Surg: Off Publ Eur Assoc Craniomaxillofac Surg* 43(7):1194–1201. doi:10.1016/j.jcms.2015.04.016
13. van Essen NL, Anderson IA, Hunter PJ, Carman J, Clarke RD, Pullan AJ (2005) Anatomically based modelling of the human skull and jaw. *Cells Tissues Organs* 180(1):44–53. doi:10.1159/000086198
14. Lovald ST, Wagner JD, Baack B (2009) Biomechanical optimization of bone plates used in rigid fixation of mandibular fractures. *J Oral Maxillofac Surg: Off J Am Assoc Oral Maxillofac Surg* 67(5): 973–985. doi:10.1016/j.joms.2008.12.032
15. Oguz Y, Uckan S, Ozden AU, Uckan E, Eser A (2009) Stability of locking and conventional 2.0-mm miniplate/screw systems after sagittal split ramus osteotomy: finite element analysis. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 108(2):174–177. doi:10.1016/j.tripleo.2009.03.051
16. Mellal A, Wiskott HW, Botsis J, Scherrer SS, Belser UC (2004) Stimulating effect of implant loading on surrounding bone. Comparison of three numerical models and validation by in vivo data. *Clin Oral Implants Res* 15(2):239–248

17. Sugiura T, Horiuchi K, Sugimura M, Tsutsumi S (2000) Evaluation of threshold stress for bone resorption around screws based on in vivo strain measurement of miniplate. *J Musculoskelet Neuronal Interact* 1(2):165–170
18. Tams J, Van Loon JP, Otten B, Bos RR (2001) A computer study of biodegradable plates for internal fixation of mandibular angle fractures. *J Oral Maxillofac Surg: Off J Am Assoc Oral Maxillofac Surg* 59(4):404–407 . doi:[10.1053/joms.2001.21877](https://doi.org/10.1053/joms.2001.21877)discussion 407-408