A Biomechanical Comparison of Three 1.5-mm Plate and Screw Configurations and a Single 2.0-mm Plate for Internal Fixation of a Mandibular Condylar Fracture

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Abstract

The most stable pattern of internal fixation for mandibular condyle fractures is an area of ongoing discussion. This study investigates the stability of three patterns of plate fixation using readily available, commercially pure titanium implants. Finite element models of a simulated mandibular condyle fracture were constructed. The completed models were heterogeneous in bone material properties, contained approximately 1.2 million elements and incorporated simulated jaw adducting musculature. Models were run assuming linear elasticity and isotropic material properties for bone. No human subjects were involved in this investigation. The stability of the simulated condylar fracture reduced with the different implant configurations, and the von Mises stresses of a 1.5-mm X-shaped plate, a 1.5-mm rectangular plate, and a 1.5-mm square plate (all Synthes (Synthes GmbH, Zuchwil, Switzerland) were compared. The 1.5-mm X plate was the most stable of the three 1.5-mm profile plate configurations examined and had comparable mechanical performance to a single 2.0-mm straight four-hole plate. This study does not support the use of rectangular or square plate patterns in the open reduction and internal fixation of mandibular condyle fractures. It does provide some support for the use of a 1.5-mm X plate to reduce condylar fractures in selected clinical cases.

Keywords
- ► finite element analysis
- ► condylar fractures
- ► ORIF

Facial fractures are a common injury often resulting from interpersonal violence or motor vehicular accident.[1] In modern surgical practice, the management of most facial fractures using the techniques of open reduction and internal fixation (ORIF) as espoused by the AO, is widely accepted as best practice; however, debate over the treatment of fractures of the mandibular condylar process continues.[2–5] The use of ORIF to treat mandibular condyle fractures is becoming

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routine.[2] Surgeons who opt to use ORIF to manage these fractures must decide on the number, size, and configuration of plates and screws to be implanted.[2,6–12] Clinically, there is tension between the desirability of using the smallest, least invasive plate possible and using an implant strong enough to provide adequate stability for fracture healing.

Finite element analysis (FEA) is a computational technique routinely used by engineers to model the mechanical behavior of man-made structures such as buildings, aircraft, and engine parts, and it is now increasingly used in biology and medicine[13–15] where analytical solutions are difficult to obtain due to complicated geometries, loading, and multiple material properties. The method treats a continuum as a finite number of interconnecting parts or elements, with the behavior of each element approximated by simplified algebraic equations that relate the behavior within the element back to the element's active nodal degrees of freedom (nodal displacements). Each element must have at least displacement continuity at the interface with other elements. From these simplifying equations, the element shape functions are defined and then used to determine the element's stiffness matrix. The individual element stiffness matrices are used to form a whole structure or global stiffness matrix which generate a large number (typically) of simultaneous equations to evaluate the displacement of all active degrees of freedom to load. From these nodal displacements, the strain and stress within all elements to the applied loads are determined.[14,16,17]

The accuracy of predictions based on a finite element model (FEM) is influenced by several variables including the accuracy of geometric replication, the number and complexity of the elements used in the model, how well material properties are captured within the elements, and the degree to which boundary conditions and loadings simulate the real-life circumstances being modeled.[12] The use of FEA to analyze the mechanics of internal fixation when applied to facial fractures is an accepted technique[12,18–25] and its usefulness in this context has been confirmed.[21,26]

Materials and Methods

A FEM of a dry cadaveric human mandible was constructed as described by the authors previously.[12] Digital Imaging and Communications in Medicine data from a computed tomographic (CT) scan of the mandible was imported into Mimics (version 13.02, Materialise, Leuven, Belgium) and separate "masks" generated for the cranium and mandible. The mandible mask was manipulated to approximate a typical subcondylar fracture with proximal and distal parts fully separated (►**Fig. 1**). Three-dimensional surface objects were generated from each mask and remeshed in Mimics to improve quality. These surface meshes were imported into Strand7 FEA software (version 2.4, Strand7 Pty Ltd, Sydney, Australia) and a volumetric mesh was created from tet4 "bricks" (low-order tetrahedral elements with four nodes) elements. The muscles were simulated using truss elements (beams that can only transmit axial loads) and these were attached to origin and insertion sites on the mandible and

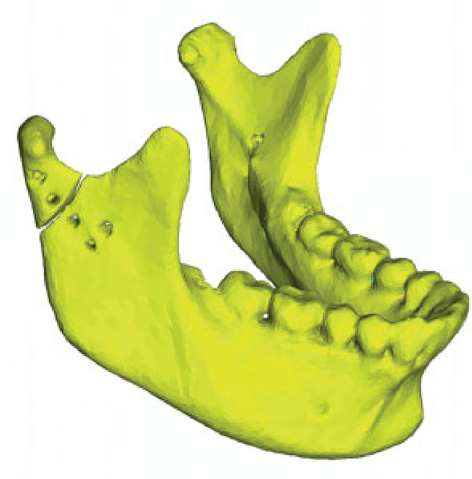

Figure 1 Finite element model of human mandible with a simulated condylar fracture.

cranium.[27] Associated muscle forces were estimated using the "dry-skull" method.[27,28] The medial pterygoid, lateral pterygoid, masseter, and temporalis muscles were modeled bilaterally with 50 muscle trusses on each side of the skull. Trusses were distributed among different muscle groups on the basis of their origin and insertion areas (►**Fig. 2**). The number and properties of trusses assigned to each muscle are shown in ►**Table 1**.

The stereolithography (STL) files of a Synthes 2.0 mm four-hole plate, a 1.5-mm X-plate, a 1.5-mm square plate, and a 1.5-mm rectangular plate were manipulated as described previously[12,29] to simulate the manual adaptation of plates to sit passively across the fracture line as occurs in clinical practice (see ►**Fig. 3**). The model assumed linear elastic material behavior and eight material properties were assigned to the skull on the basis of bone density as determined by Hounsfield units from the CT scan (►**Table 2**).[30] Each completed model contained approximately 1.2 million elements.

A linear static solve was undertaken on each model in Strand7 and the distribution of von Mises (VM) stress of the relevant plate and screw configuration was determined, as well as the relative movement between the fracture fragments as described previously.[12] Comparative analyses of the VM stress distribution and relative displacement between the fractured fragments allow a prediction of which configuration is most stable compared with the other patterns of plate fixation considered in this study. It is likely that a lower volume weighted mean VM stress and lower relative interfragmentary movement would be associated with more stable fixation. It was assumed that relative interfragmentary motion of greater than 150 μm would be a marker for an increased risk of clinical problems with fracture healing.[23–25,31]

Results

The relative displacements of the proximal and distal fragments compared with the volume weighted mean VM stress

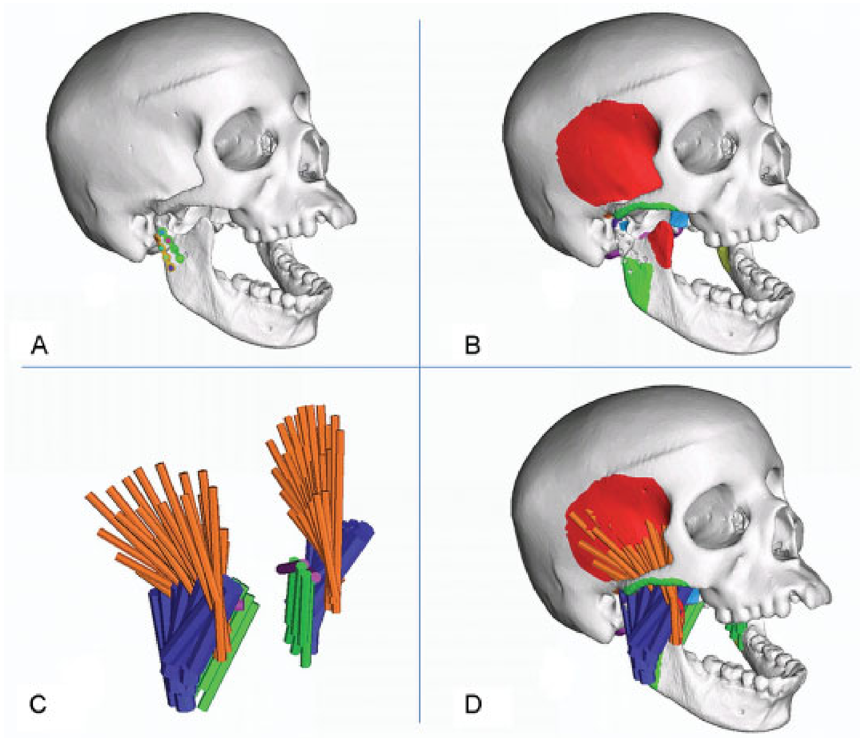

Figure 2 (A) Brick model of skull and mandible including plates and screws. (B) Colored regions showing attachment and insertion areas for different muscle groups. (C) Truss elements simulating muscle fibers. (D) Final preprocessed FE model ready to be solved.

of each plate configuration are given in ►**Table 3**. The VM stress distributions predicted in the plates and the mandible are graphically displayed in ►**Figs. 3** and **4**.

The results indicate that of 1.5-mm midface plates investigated, the X plate is the most stable followed by the square plate and then the rectangular plate. The graphical representation of surface VM stress (►**Fig. 4**) shows that the X plate has the lowest overall spread of stress when compared with the rectangular and square 1.5-mm plates. Of interest is the fact that the X plate's mechanical performance was very similar to that of the 2.0-mm four-hole single mandibular plate, even though the X plate is thinner and more easily bent to passively fit the reduced fracture fragments. We have previously shown that two parallel 2.0-mm four-hole plates were more stable than a single 2.0-mm four-hole plate in a FEM of a mandibular condyle fracture.[12] The relative movements predicted in this study for both the 2.0-mm four-hole single plate and the 1.5-mm X plate were 113.9 and 115.8 µm, respectively. This lends some comfort to clinicians who might choose to use a single plate or an X plate due to anatomical exigencies in some cases of mandibular condyle fractures. As the X plate in this study was essentially equivalent in performance to the single 2.0-mm four-hole plate, we would still advise that where clinically possible, two plates—parallel straight 2.0-mm configuration as described previously—be used when managing condylar fractures.[12]

Discussion

Treatment of mandibular condyle fractures has evolved from one of essentially closed reduction in the past to the present time in which many clinicians advocate ORIF for a significant proportion of these injuries. Apart from the debate over closed versus open treatment, there is also discussion within the literature as to the optimal number, type, and configuration of plates and screws to use when ORIF is chosen as the mode of treatment.[6–8,10,12,32–36] Our work improves on previous FEM of mandibular condyle fracture plating

Table 1 Properties of muscle trusses assigned to model

	Number of truss elements on one side	Force/truss (*N*)	Truss diameter (mm)	Young modulus (MPa)	Density (T/mm^3)
Medial pterygoid	6	3	5	0.1	1×10^{-09}
Lateral pterygoid	2	3	5	0.1	1×10^{-09}
Masseter	11	17.91	8.72	0.1	1×10^{-09}
Temporalis	31	3.58	3.90	0.1	1×10^{-09}

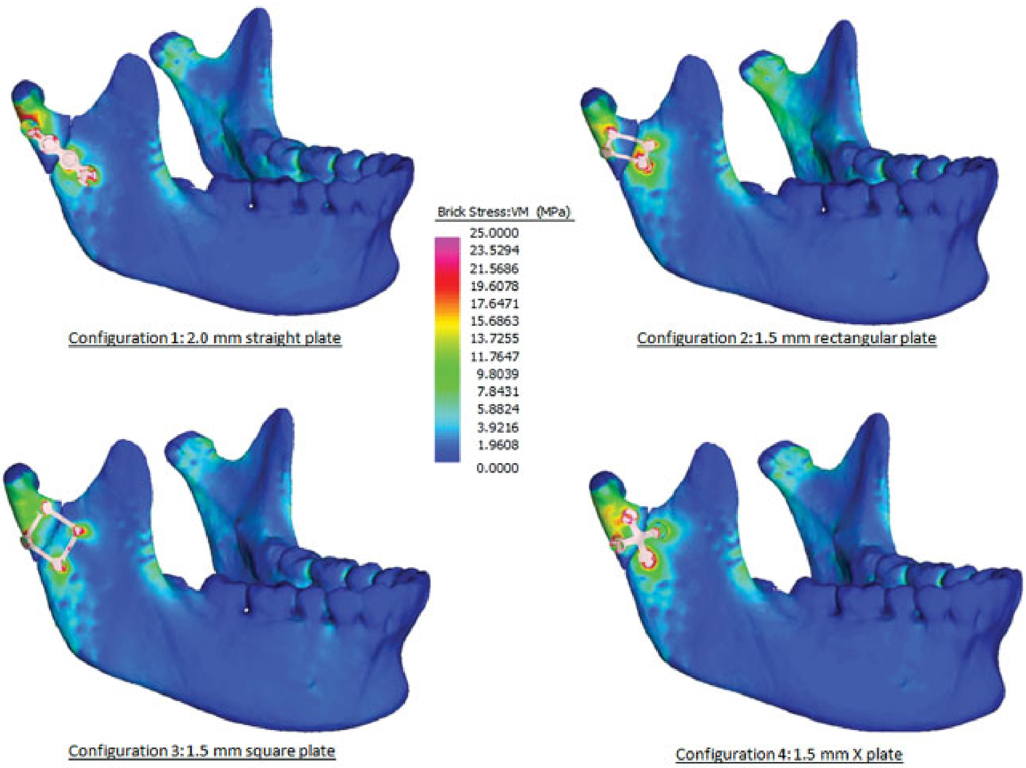

Figure 3 Solved finite element models showing the four plates and screw configurations tested and the volume-weighted mean Von Mises stresses.

configurations, as it includes the mandible and cranium as an articulated unit, more accurately models the architectures of the jaw musculature, and differentiates between cancellous and cortical bone.[36] In addition, the model used in our study more realistically replicates the surgical procedure, as the virtual plates are "bent" to sit passively on the reduced fracture fragments and each screw models the mechanical interface between bone and implant. With the exception of the author's previous models,[12] this has not been done with other published models.

Table 2 Allocation of material properties to brick elements in the FEM according to the Hounsfield units distribution in the CT scan

Brick material properties	Young modulus (MPa)	Density (T/mm^3)
Material 1	1,527	2.508×10^{-10}
Material 2	1,868.6	2.916×10^{-10}
Material 3	2,223.4	3.325×10^{-10}
Material 4	10,786.8	1.094×10^{-09}
Material 5	21,734.2	1.855×10^{-09}
Material 6	27,082.2	2.190×10^{-09}
Material 7	32,704.3	2.525×10^{-09}
Material 8	38,575.4	2.860×10^{-09}

Abbreviations: CT, computed tomography; FEM, finite element model.

The size of the models used in this study is considerably larger than other comparable models of the human mandible. Models used in the present study each comprise around 1.2 million elements and are heterogeneous, while other models have 47,525 elements with 72,899 nodes and homogeneous,[22] 59,000 elements with 14,000 nodes and homogeneous,[23] 130,259 elements and homogeneous,[37] and 7,700 elements with 11,500 nodes and homogeneous.[38] All else being equal, for geometrically complex structures that have significant heterogeneous properties, the predictive accuracy of a FEM tends to increase with increasing number of brick elements.[14,30] Another advantage of this FEM is that the force vectors applied to the model have been designed to simulate the forces applied by the musculature attached to the mandible. When compared with testing plate configurations in a

Table 3 Relative interfragmentary movement and volume-weighted mean VM stress of each plate configuration

	Relative movement, µm (SD)	Volume-weighted mean VM stress	Plate volume (mm^3)
Straight plate	113.9 (54.3)	78.7	64.4
Rectangular plate	330.9 (42.4)	312.6	21.0
Square plate	269.0 (6.86)	198.8	28.6
X plate	115.8 (65.6)	119.0	44.8

Abbreviations: SD, standard deviation; VM, von Mises.

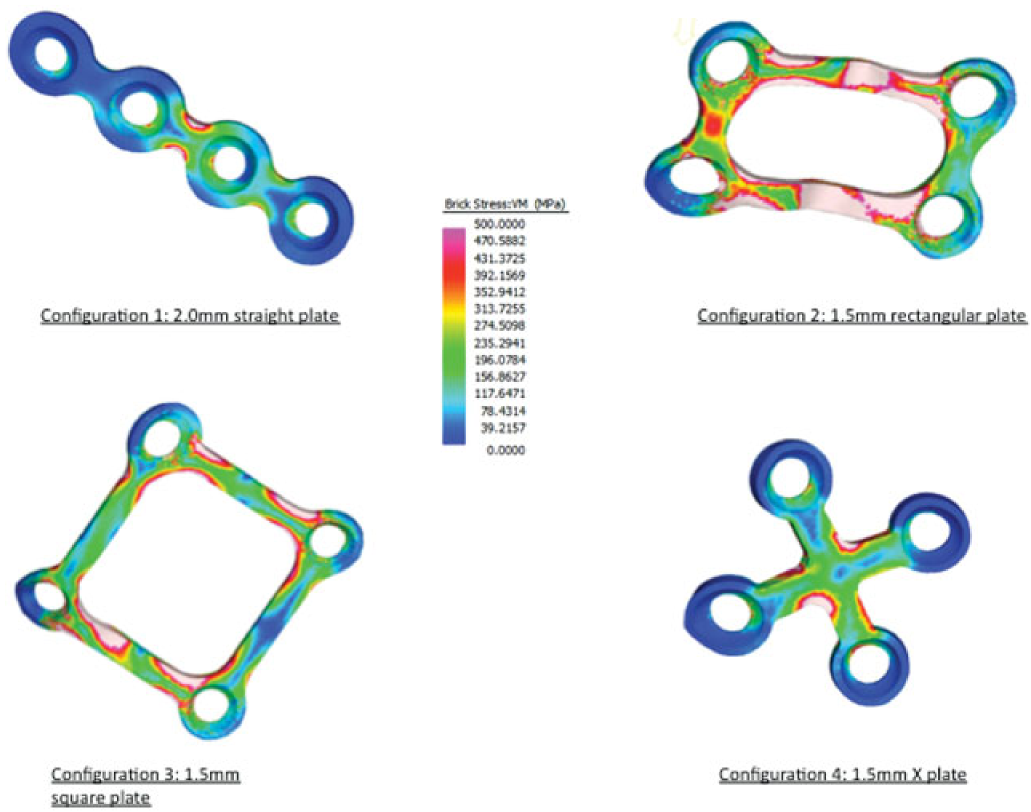

Figure 4 Solved finite element models of each plate type used showing the volume-weighted mean Von Mises stresses.

conventional mechanical testing system, this FEM results in a more realistic pattern of physiological loading.

Notwithstanding some literature proposing no real advantage of ORIF versus closed reduction of mandibular condyle fractures,[4] the trend of recent articles points to superior results of ORIF over closed reduction in selected cases.[2,5,10,39]

The debate concerning what type of internal fixation is most appropriate continues. In general, the trend of the literature suggests that thicker plates are more stable than thinner plates,[9,11] that bicortical screws are more stable than monocortical screws,[9] and that two plates are more stable than a single plate.[9,10,12,19,33,36,40]

The clinical experience of one of the authors (P.A.) has been that it is sometimes difficult to place two straight plates in a suitable pattern due to space considerations, especially if an endoscopic technique is used. Also, commonly the straight plates used are plates usually employed for mandibular body, angle, or parasymphyseal fractures and they are relatively thicker and harder to accurately bend to conform to the complex three-dimensional shape of the condylar neck than are thinner midface plates. Bearing this in mind, this study was undertaken to see if any data supported the use of thinner midface plates which are smaller and easier to manipulate.

With a relative movement of 269.0 and 330.9 µm, the square and rectangular plates (respectively) cannot be recommended in the ORIF of mandibular condyle fractures. In contrast, with a relative interfragmentary movement of 115.9 µm (standard deviation 65.7), the X plate may be clinically useful in selected cases, and further studies are indicated with respect to this. The X plate had approximately 70% of the volume of the 2.0-mm straight plate, yet achieved an essentially identical degree of stability and a similar volume-weighted mean VM stress (within error). This may mean that the X plate is a more efficient shape at reducing condylar fractures and further developmental work regarding this is being undertaken. Further work is also needed to validate these results against experimental data. We are presently engaged in efforts to achieve broad validation using both nonhuman and human mandibles.

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