# In Silico Analysis of the Biomechanical Stability of Commercially Pure Ti and Ti-15Mo Plates for the Treatment of Mandibular Angle Fracture

*Satoshi Yamaguchi, PhD,* Rodolfo B. Anchieta, DDS, PhD,† Fernando P. S. Guastaldi, DDS, PhD,‡ Nick Tovar, PhD,§ Daisuke Tawara, PhD,|| Satoshi Imazato, DDS, PhD,¶ and Paulo G. Coelho, DDS, PhD#*

**Purpose:** To investigate the influence of different materials and fixation methods on maximum principal stress (MPS) and displacement in reconstruction plates using in silico 3-dimensional finite element analysis (3D-FEA).

**Materials and Methods:** Computer-assisted designed (CAD) models of the mandible and teeth were constructed. Champy and AO/ASIF plates and fixation screws were designed with CAD software. 3D-FEA was performed by image-based CAE software. Maximum and minimum values of biomechanical stability, MPS, and displacement distribution were compared in Champy and AO/ASIF plates made from commercially pure titanium grade 2 (cp-Ti) and a titanium-and-molybdenum (14.47% wt) alloy (Ti-15Mo).

**Results:** For plates fixed on a model of a fractured left angle of the mandible, the maximum and minimum values of MPS in the cp-Ti–constructed Champy plate, upper AO/ASIF plate, and lower AO/ASIF plate were 19.5 and 20.3%, 15.2 and 25.3%, and 21.4 and 4.6% lower, respectively, than those for plates made from Ti-15Mo. In the same model, the maximum and minimum values of displacement in the cp-Ti–constructed Champy plate, upper AO/ASIF plate, and lower AO/ASIF plate were 1.6 and 3.8%, 3.1 and 2.7%, and 5.4 and 10.4% higher, respectively, than those for plates made from Ti-15Mo.

**Conclusions:** This in silico 3D-FEA shows that Ti-15Mo plates have greater load-bearing capability.

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Mandibular angle fractures most commonly occur in 20- to 40-year-old men, generally as the result of personal assault, falls, or motorized vehicle accidents.[1,2] Treatment of these fractures is challenging because of the difficulty of treating a sensitive load-bearing region that is susceptible to infection. In recent years,

*Associate Professor, Department of Biomaterials Science, Osaka University Graduate School of Dentistry, Osaka, Japan.

†Assistant Professor, Centro Universotário do Norte Paulista (UNORP), São José do Rio Preto, SP, Brazil.

‡Postdoctoral Research Fellow, Faculdade de Odontologia de Araraquara, UNESP - Universidate Estadual Paulista, Araraquara, SP, Brazil.

§Assistant Professor, Department of Biomaterials and Biomimetics, New York University, New York, NY.

||Assistant Professor, Department of Mechanical and Systems Engineering, Ryukoku University, Shiga, Japan.

¶Professor, Department of Biomaterials Science, Osaka University Graduate School of Dentistry, Osaka, Japan.

#Associate Professor, Department of Biomaterials and Biomimetics, New York University, New York, NY.

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Address correspondence and reprint requests to Dr Yamaguchi: Department of Biomaterials Science, Osaka University Graduate School of Dentistry, 1-8 Yamadaoka, Suita, Osaka 565-0871, Japan; e-mail: yamagu@dent.osaka-u.ac.jp

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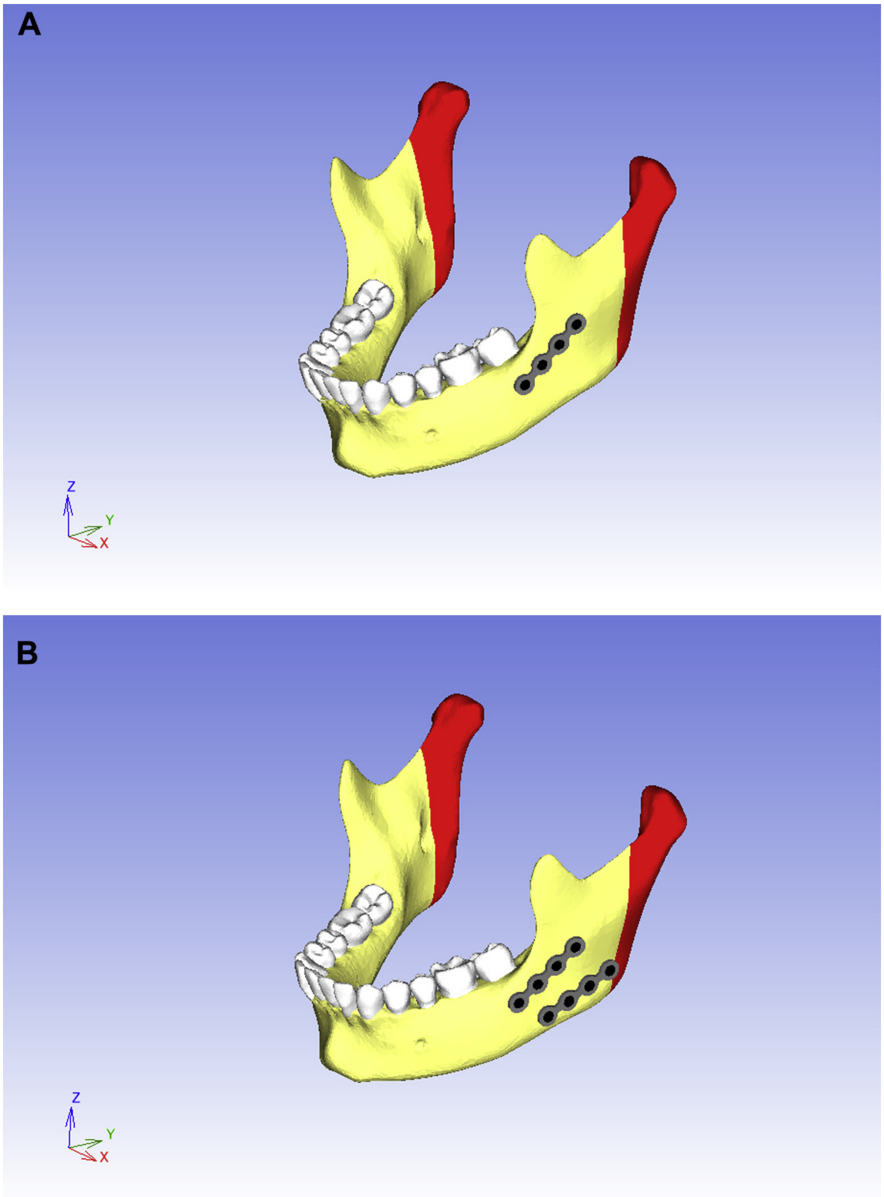


**FIGURE 1.** Computer-assisted designed models used for in silico finite element analysis of *A*, Champy and *B*, AO/ASIF plates. The models depict the mandible (*yellow and red*), teeth (*white*), plate (*light gray*), and screws (*dark gray*).

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validation studies have been conducted to develop optimized reconstruction plates with appropriate mechanical properties and therefore shorten the healing period of the fracture.[3] Precise evaluation of the mechanical stresses that develop in a fractured mandible is essential to this optimization process.

There are 2 main avenues to decreasing stress shielding and damage to the blood supply in fractured bone.[4-7] The first is to modify the bone-plate material. The second is to decrease contact between the bone and the plates. Few studies have investigated the combined effects of these 2 parameters on stress shielding in the fractured bone.[6]

Different internal fixation devices are used to promote the stabilization of bone structure.[5,8] Reconstruction plates should be biocompatible and have appropriate mechanical properties for the support of fractured bone.[5-7,9,10] Conventional reconstruction plates are fabricated from metals such as cobalt-and-chromium, stainless steel, and titanium alloys. These plates have acceptable biocompatibility, provide excellent reduction of bone fragments, and have the required strength to stabilize and support the fracture. Titanium alloys also are the preferred material for the manufacture of miniplates and screws because of their stiffness, strength, and

**Table 1. MATERIAL PROPERTIES USED FOR IN SILICO FINITE ELEMENT ANALYSIS**

| | Mandible and Teeth | cp-Ti Plate | Ti-15Mo Plate | Ti-6Al-4V Screw |
|---|---|---|---|---|
| Young modulus (MPa) | 624.24 | 107,000 | 75,000 | 110,000 |
| Poisson ratio | 0.2817 | 0.34 | 0.34 | 0.34 |

*Note:* The Young modulus and Poisson ratio represent elasticity of materials.
Abbreviations: cp-Ti, commercially pure titanium grade 2; Ti-15Mo, titanium-and-molybdenum (14.47% wt) alloy.

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biocompatibility, which help these devices to maintain the relative position of bone segments. Ti-15Mo—a titanium-and-molybdenum system alloy containing 14.47% wt molybdenum—exhibits high corrosion resistance, high electrochemical stability, and excellent biocompatibility[11] closer to commercially pure titanium grade 2 (cp-Ti).[12] For elastic modulus, Ti-15Mo closely approximates that of human bone (~30 GPa),[13] unlike cp-Ti.

The primary goal of a bone plate is to provide maximum stability in the bone fracture region with the minimum amount of implanted material. Achieving this goal decreases patient complications and overall patient discomfort. Greater biomechanical understanding allows the designer to take a more structured perspective on the design and composition of bone plates.[4] Three-dimensional finite element analysis (3D-FEA)—a computational technique originally developed by engineers to model the mechanical behavior of structures such as buildings, aircraft, and engine parts—can determine the displacements, stresses, and strains over an irregular solid body given the complex material behavior and loading conditions imposed on that body. 3D-FEA has been used to evaluate the treatment of facial fractures[9,14-16] and its use in evaluating plating techniques has been shown to be promising.[9]

The aim of this study was to use in silico 3D-FEA to investigate maximum principal stress (MPS) and displacement in 2 types of reconstructive fixation plate (Champy and AO/ASIF) made from 2 types of material (cp-Ti and Ti-15Mo).

## Materials and Methods

### COMPUTER-ASSISTED DESIGNED MODELS SIMULATING ANGLE FRACTURES

Computer-assisted designed (CAD) models of the mandible and teeth for in silico 3D-FEA were constructed from a 3D whole-body human adult male model.[17] Plates (Champy and AO/ASIF types) and fixation screws were designed with CAD software (Solidworks 2011; Dassault Systèmes Solidworks Corp, Waltham, MA; Fig 1). Each 1.0-mm-thick plate included 4 screw holes 2.0 mm in diameter. The Champy plate was fixed to the isolated left angle of mandible model by 4 φ2.0- × 6.0-mm screws made of $\alpha$-$\beta$ titanium alloy (Ti-6Al-4V; ASTM F136-12a). The AO/ASIF system consisted of upper and lower plates fixed to a model of the isolated left angle of the mandible by 4 φ2.0- × 6.0-mm Ti-6Al-4V screws (upper plate) and 4 other screws of φ2.0 × 12.0 mm (lower plate).

### THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

3D-FEA was performed by image-based CAE software (VOXELCON2015; Quint Corp, Tokyo, Japan). Material properties used for 3D-FEA are listed in Table 1. The voxel numbers of each CAD model are presented in Table 2. The mandibular rami were fixed and a 3.0-mm force displacement corresponding to a maximum failed load of an in vitro experiment[18] was applied through the vertical axis of the mandibular central incisors (Fig 2). For the evaluation of biomechanical stability, the authors measured the MPS used as a failure criterion of titanium alloy[19,20] and displacement distribution in models reconstructed

**Table 2. NUMBER OF VOXELS FOR COMPONENTS OF FINITE ELEMENT MODELS**

| | Mandible | Teeth | Upper Plate | Bottom Plate | φ2.0- × 6.0-mm Screw | φ2.0- × 12-mm Screw |
|---|---|---|---|---|---|---|
| Champy | 35,955,373 | 7,966,020 | 83,665 | — | 39,990 | — |
| AO/ASIF | 35,909,282 | 7,966,020 | 83,665 | 83,271 | 39,990 | 89,214 |

*Note:* Voxel resolution was standardized to 0.1 mm.

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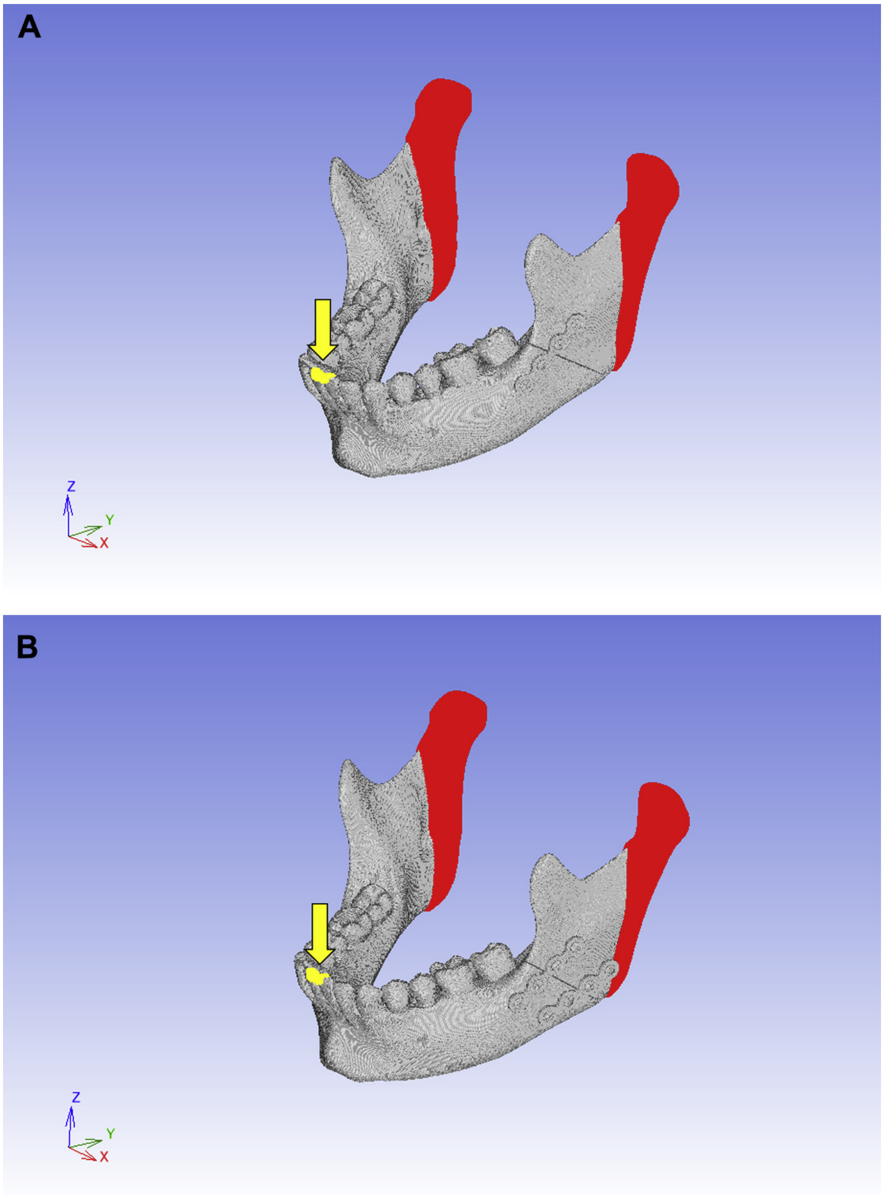


**FIGURE 2.** Voxel models and boundary conditions used for in silico finite element analysis of *A*, Champy and *B*, AO/ASIF plates. The images display loaded areas (*yellow*), the direction of force (*arrows*), and fixed areas (*red*).

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with Champy and AO/ASIF plates made from cp-Ti (ASTM F67-06) or Ti-15Mo (ASTM F2066-08). Maximum and minimum values were acquired of each of these parameters.

## Results

### MAXIMUM PRINCIPAL STRESS

Table 3 presents maximum and minimum values of MPS in plates made from cp-Ti and Ti-15Mo. The maximum and minimum values of MPS in the Champy plate, upper AO/ASIF plate, and lower AO/ASIF plate were 19.5 and 20.3%, 15.2 and 25.4%, and 21.4 and 4.56% higher, respectively, in plates made from cp-Ti than in those made from Ti-15Mo. For the cp-Ti and Ti-15Mo Champy plates, the maximum and minimum values of MPS were observed in the upper middle and lower middle areas of the plates, respectively (Fig 3). For AO/ASIF plates (irrespective of material), the maximum MPS values were observed in the upper middle section of the upper plate, whereas the minimum MPS values were found inside the first screw hole on the bottom plate (Fig 4).

### DISPLACEMENT

Table 4 presents maximum and minimum values of displacement occurring in plates made from cp-Ti and

**Table 3. MAXIMUM/MINIMUM VALUES OF MAXIMUM PRINCIPAL STRESS (MEGA PASCALS) IN PLATES MADE FROM CP-TI AND TI-15MO**

| | cp-Ti | Ti-15Mo |
|---|---|---|
| Champy | 1,226.0/−149.7 | 986.8/−119.3 |
| AO/ASIF | | |
| Upper plate | 1,037.9/−83.8 | 879.8/−62.6 |
| Lower plate | 623.1/−182.0 | 489.6/−173.7 |

Abbreviations: cp-Ti, commercially pure titanium grade 2; Ti-15Mo, titanium-and-molybdenum (14.47% wt) alloy.

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Ti-15Mo. The maximum and minimum values of displacements in the Champy plate, upper AO/ASIF plate, and lower AO/ASIF plate were 1.6 and 3.8%, 3.1 and 2.7%, and 5.4 and 10.4% higher in Ti-15Mo plates than in cp-Ti plates. Irrespective of material, maximum values of displacement in Champy plates were observed at the mesial end of the plate, whereas minimum values were observed at the distal end (Fig 5). In the AO/ASIF model, maximum values of displacement were found at the proximal end of the upper plate, whereas minimum values were obtained from the distal sections of the lower plate, regardless of material (Fig 6).

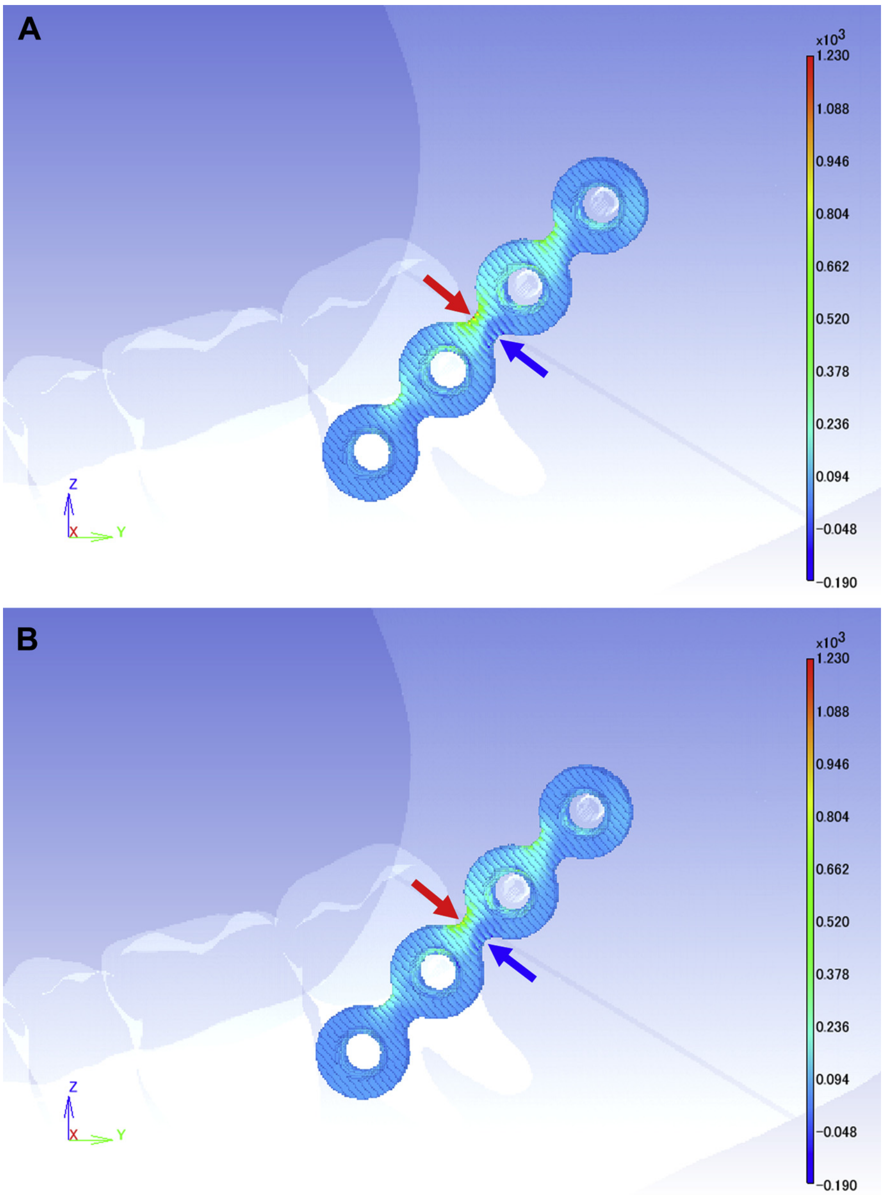


**FIGURE 3.** Maximum principal stress distribution obtained in Champy plates fabricated from *A*, commercially pure titanium grade 2 and *B*, titanium-and-molybdenum (14.47% wt) alloy. Images depict the positions of the maximum (*red arrows*) and minimum (*blue arrows*) values of the maximum principal stresses in these Champy plates.

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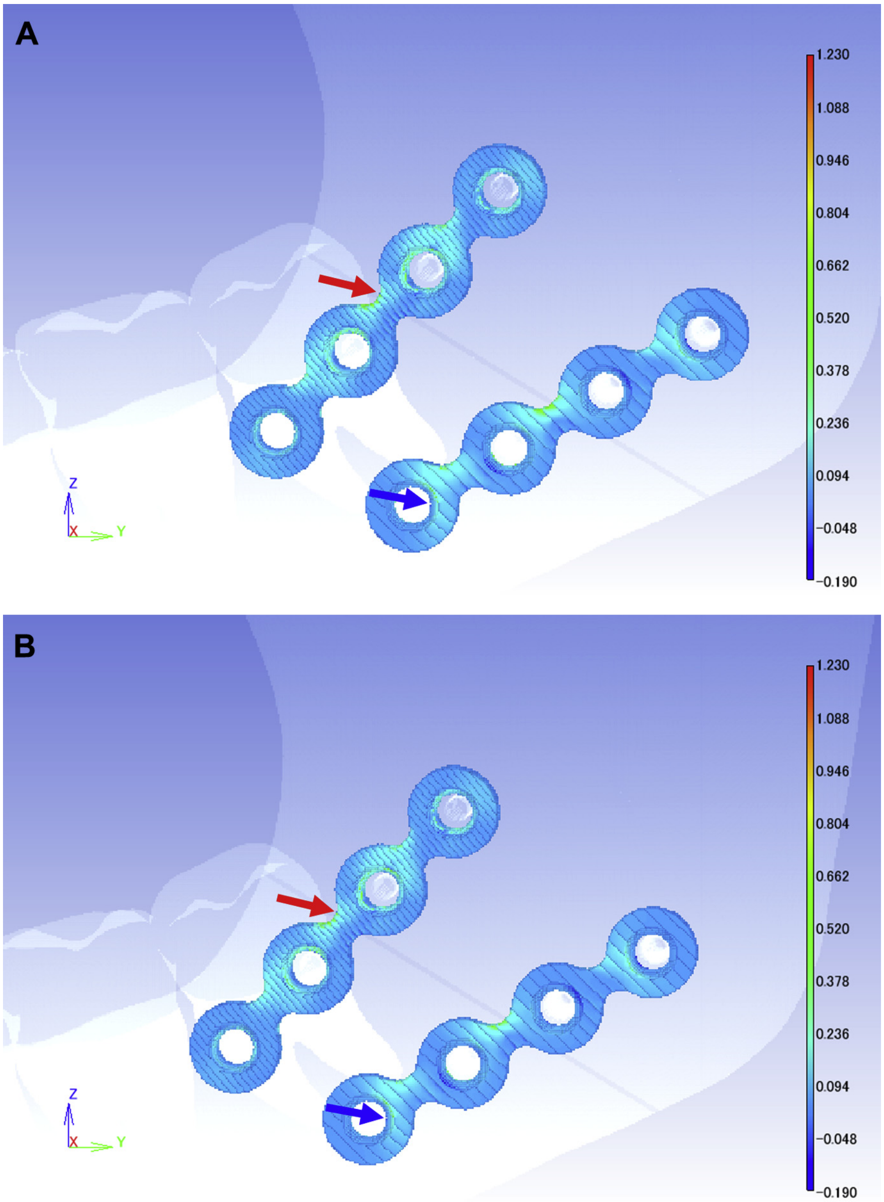


**FIGURE 4.** Maximum principal stress distribution obtained in AO/ASIF plates fabricated from *A*, commercially pure titanium grade 2 and *B*, titanium-and-molybdenum (14.47% wt) alloy. Images depict the positions of the maximum (*red arrows*) and minimum (*blue arrows*) values of the maximum principal stresses in these AO/ASIF plates.

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## Discussion

A previous in vitro single-load failure test of a synthetic mandible model concluded that AO/ASIF plates made of Ti-15Mo were more resistant to load and displacement than Champy plates.[18] However, the mechanism by which this improved resistance was conferred could not be determined. The present in silico study presented the distribution of stress and displacement in reconstruction plates and investigated the biomechanical stability of Champy and AO/ASIF plates fabricated from cp-Ti and Ti-15Mo.

Von Mises stress is a superior failure criterion for ductile materials such as metals during in silico analysis. However, because of the scalar nature of its values, von Mises stress cannot determine whether observed stresses are compressive or tensile. MPS—a vector value—is a useful parameter for identifying the location(s) of those compressive and tensile stresses. Displacement observed in the reconstruction plates is helpful to understand the relative displacement of fractured bones. In this study, MPS and displacement were calculated by 3D-FEA to evaluate

**Table 4. MAXIMUM/MINIMUM VALUES OF DISPLACEMENT (MILLIMETERS) IN PLATES MADE FROM CP-TI AND TI-15MO**

| | cp-Ti | Ti-15Mo |
|---|---|---|
| Champy | 0.852/0.0684 | 0.866/0.0710 |
| AO/ASIF | | |
| Upper plate | 0.513/0.150 | 0.529/0.154 |
| Lower plate | 0.314/0.0308 | 0.331/0.0340 |

Abbreviations: cp-Ti, commercially pure titanium grade 2; Ti-15Mo, titanium-and-molybdenum (14.47% wt) alloy.

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the biomechanical stability of the plate types used in treatment of mandibular angle fracture.

Ti-15Mo plates have been shown to exhibit lower MPS and higher tensile strength than plates made from cp-Ti,[21,22] strongly suggesting that Ti-15Mo provides greater resistance than cp-Ti for a same amount of load and displacement. Furthermore, the maximum and minimum values of MPS were focused in the upper middle and lower middle of the Champy plate, respectively, characteristic of a flexural mode of stress. Conversely, the concentration of maximum and minimum forces in the AO/ASIF plates suggested that they might inhibit flexural stress.

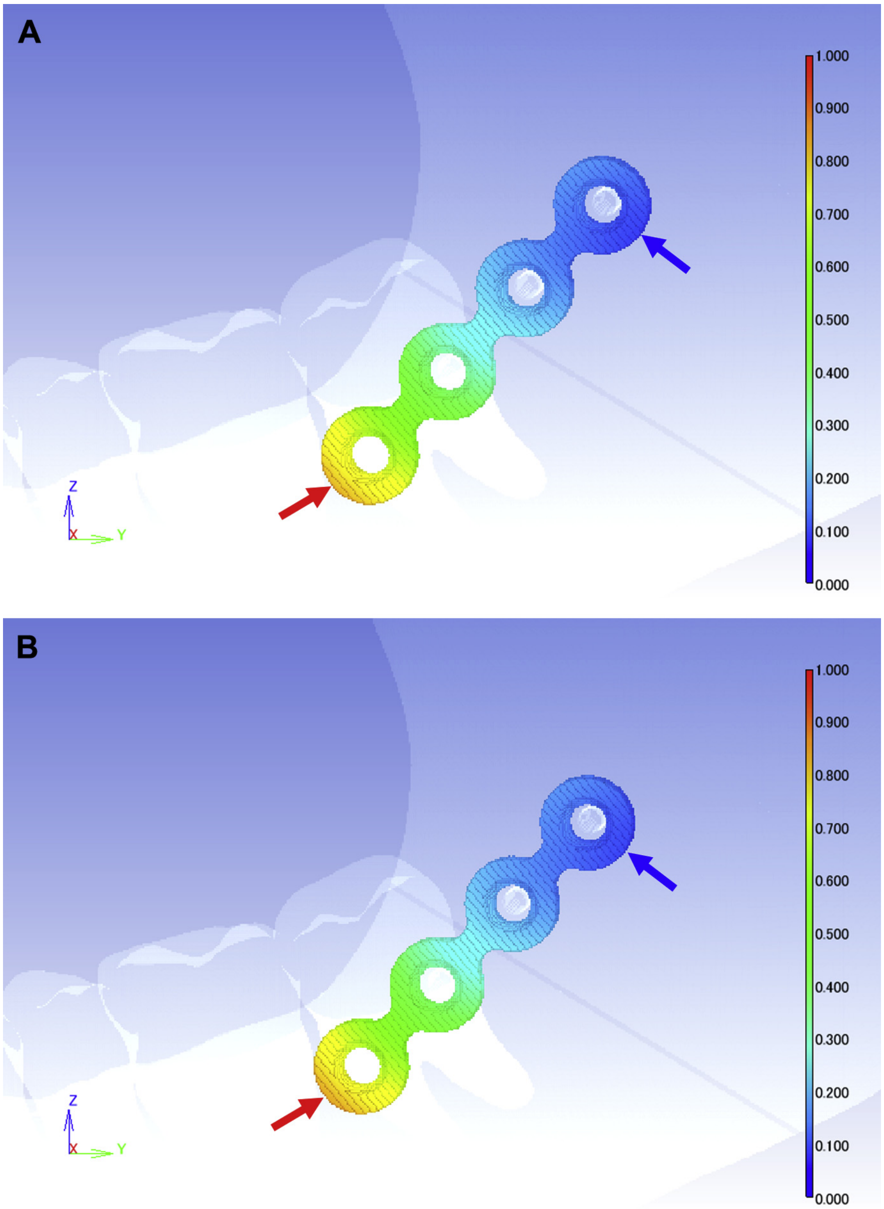


**FIGURE 5.** Displacement distribution obtained in Champy plates fabricated from *A*, commercially pure titanium grade 2 and *B*, titanium-and-molybdenum (14.47% wt) alloy. Images depict the positions of the maximum (*red arrows*) and minimum (*blue arrows*) values of displacement.

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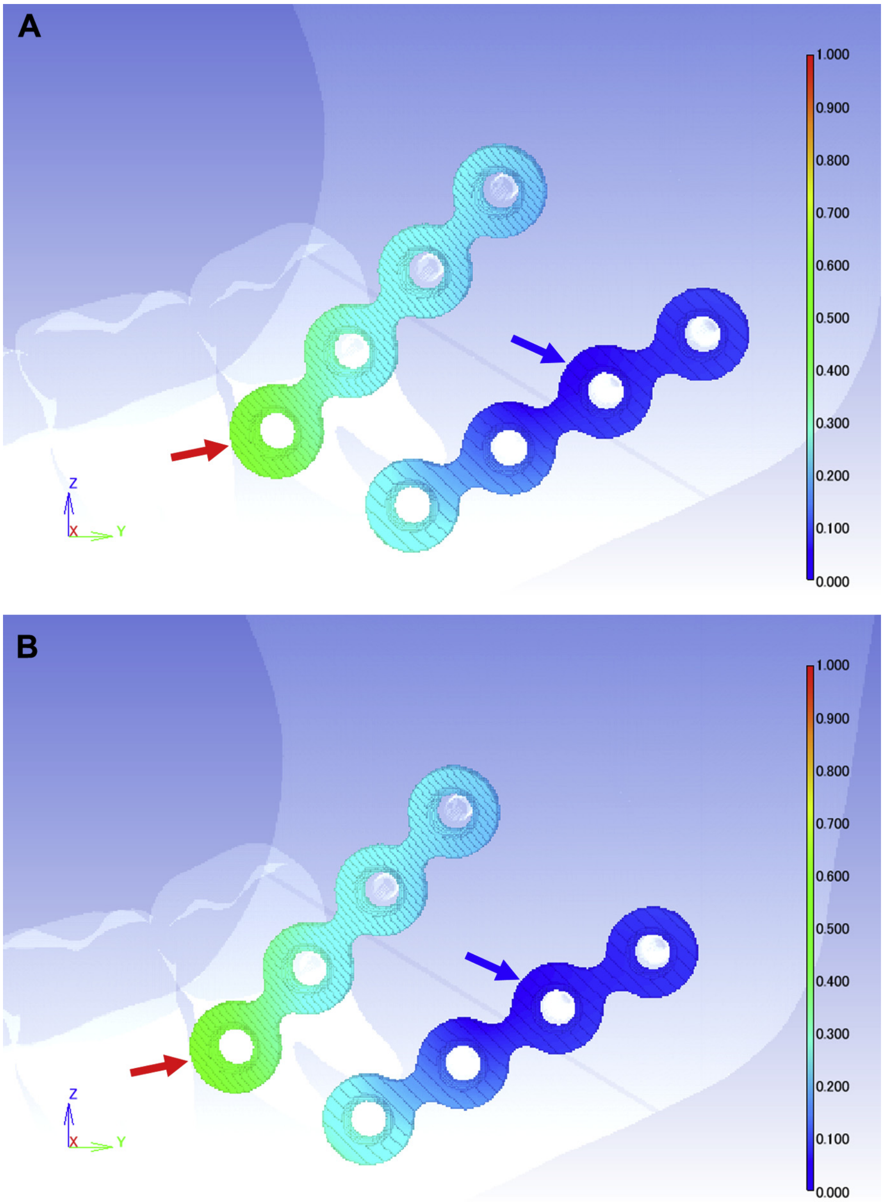


**FIGURE 6.** Displacement distribution obtained in AO/ASIF plates fabricated from *A*, commercially pure titanium grade 2 and *B*, titanium-and-molybdenum (14.47% wt) alloy. Images depict the positions of the maximum (*red arrows*) and minimum (*blue arrows*) values of displacement.

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The addition of molybdenum to titanium is believed to decrease the Young modulus of the resultant alloy[23-25]and give it similar material properties to human mandibular bone.[26] For the Champy plate and the upper AO/ASIF plate, the maximum and minimum values of displacement were observed in peripheral areas of the plates, whereas the minimum displacement in the lower AO/ASIF plate was shifted toward the middle of the plate. This altered center of rotation in the lower AO/ASIF plate could decrease the relative displacement of the fractured bones it re-apposes. There is further scope to improve this stability by optimizing the position and orientation of the plates. However, the use of 2 plates rather than 1 plate represents an increased risk of complications.[4] Ti-15Mo has properties that make it superior to Ti-6Al-4V as the material from which the screws are fabricated, notably that it has similar material properties to human mandibular bone[18] and appears to inhibit the strain concentration that induces bone resorption.[27]

Within the limitations of in silico 3D-FEA (ie, the linear properties used for the mandible and teeth), the present results suggest that Ti-15Mo is a suitable material for bone reconstruction plates. Further in silico studies considering anisotropic and nonhomogeneous properties of the mandible[28,29] could be helpful in further optimizing fracture fixation methods for patients.

This in silico 3D-FEA showed that plates made from Ti-15Mo possess greater load-bearing capacity than those made from cp-Ti. From these findings, it can be predicted that the superior performance of Champy plates made from Ti-15Mo could enable a shorter treatment period with greater longevity in clinical service.

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