Finite Element Analysis of Temporomandibular Joint Implant Under Five Simulated Clenching Loads

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Finite element analysis of TMJ implant under five simulated clenching loads

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The temporomandibular joint is one of the most complex anatomical structures and is exposed to high stress conditions during daily movements. Replacing the joint is normally done only in severe cases as success rate of the replaced joint is not as encouraging as other joint replacements. The design of TMJ implant which includes material selection plays a significant role in its success. Two different biomaterials – Ti-6Al-4V and CoCrMo – under static loads simulating five clenching tasks were analysed in this study. A three dimensional model of an adult mandible was developed from Computed Tomography image dataset, as well as a generic TMJ implant with fixation. All the applied clenching tasks consisted of nine principle muscles. The results showed that both materials were safe under these loading conditions. However Ti-6Al-4V showed a comparatively lower stress level.

1. INTRODUCTION

Temporomandibular joint (TMJ) is a bilateral ginglymoarthroidal joint which attaches the maxilla to the mandible that enables daily movements such as speech, chewing, swallowing, and snoring. [1] It is one of the most important joints in the human body as it is one of the most frequently used joints. [2]

There are a large number of diseases which can affect TMJ and cause TMJ disorders (TMD). Studies on TMD confirmed that 20–25% of American people are expected to have TMD symptoms. [3] Total TMJ reconstruction was developed to treat severely disabled TMJ joint and improves the function of the mandible. [4-11] The replacement normally composed of a condylar implant with an articulating glenoid fossa, in which the non-functional joint is removed and placed by an artificial one. [1]

Due to the complex nature of the joint, a successful implant requires due consideration in terms of the chosen material as well as the geometry. [12-14] Several simulation studies have been reported in the study of the TMJ and implants for its replacement through mathematical model or finite element analysis. [15-19] However, comprehensive analysis of TMJ implants appeared to be lacking. [20] The aim of this study was therefore to analyze TMJ implant made of different biomedical materials under simulated clenching loads via the finite element method. This method is an established tool and has been widely used in orthopaedics [21-23] and dentistry. [24]

2. MATERIALS AND METHODS

An adult mandible was scanned via a Computed Tomography scanner (Siemens Somatom Sensation 16, Siemens AG, Germany) with a slice thickness of 1mm, resolution of 512 x 512 and pixel size of 0.418 mm. The image dataset was loaded to an image processing software package (Mimics, Materialise NV, Leuven, Belgium) where the cortical and cancellous bones of the mandible were separated. The three-dimensional (3D) model of the lower jaw was then transferred to a commercial 3D modeling software (SolidWorks 2009, Dassault Systèmes, USA).

Three dimensional model of a commercial TMJ implant (TMJ Implants, Inc.,Golden, CO, USA) was developed with the dimensions taken from other published work. [25] The implant stem was set to a thickness of 2.5mm and length 44.6mm. The diameter of the implant condyle was set at 8.7mm and length/height of 10.03mm. The diameter of all ten screw holes were set at 3.02mm. To simulate TMJ replacement, the condylar part of the joint was cut and the implant was located at the osteotomy site. Three screws were used for fixation of the implant to the mandible as previous reports showed that three screws were sufficient to provide optimum stability. [26] The three screws had a diameter of 3mm each (Fig. 1A).

FEM was used for static analysis of the model via the software Cosmosworks (CosmosWorks 2009, Dassault Systèmes, USA). The model was meshed using parabolic tetrahedral elements with a size of 1.2mm for the mandible and 0.8mm for the implant and screws (Fig. 1A). The total number of elements and nodes were 156,165 and 231,724, respectively.

Material properties of two different biomaterials were assigned to the plate – Ti-6Al-4V and cobalt-chromium-molybdenum alloy (CoCrMo). Titanium alloy (Ti-6Al-4V) properties were assigned for the screws. All material properties were considered to be homogenous, isotropic and linearly elastic (Table 1). The material properties of all components were taken from previous published data. [27 28 29] Screws were considered to be completely surrounded by cortical bone with an assigned touching contact condition.

Static loading conditions were applied to simulate five different clenching tasks. [30] The loading formations were composed of nine major muscles: superficial masseter, deep masseter, medial pterygoid, anterior temporalis, middle temporalis, posterior temporalis, inferior lateral pterygoid, superior lateral pterygoid, and anterior digastrics. These muscles occupy a wide area of attachment symmetrically. To construct pairs of muscle forces, a set of parallel vectors were bilaterally loaded to the jaw model at their locations (Fig. 1B). The unit vectors of muscular forces were taken from the work of Korioth et al. and their related maximum magnitudes [30] are presented in Table 2. Each static biting task has been assimilated as follows:

(1) Clenching in the intercuspal position (ICP); in which the canines, premolars and molars were bilaterally and vertically restrained from movement (excluding the right third molar, which was partially erupted);
(2) Clenching with the teeth in left group function (LGF), in which the left canines, premolars, and molars were vertically restrained;
(3) Clenching in left group function with a cross-arch balancing contact on the second molar (LGF+B), in which the left canines, premolars, and molars were vertically restrained. In addition to these teeth, the right second molar was also restrained;
(4) Incisal clenching (INC), in which four incisors were not allowed to translate upward;
(5) Right unilateral molar clenching (RMOL), in which the first right molar was not allowed to translate upward.

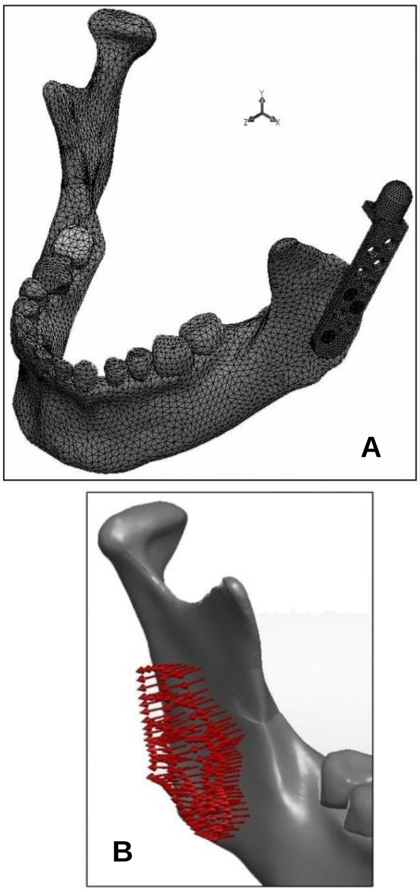

Fig. 1. (A) Simulated TMJ replacement, (B) A group of parallel vectors on the right ramus to simulate the masseter muscle loads.

Table 1. Assigned material properties for the FEA model.

Material	Elastic Modulus [MPa]	Poisson's ratio	Yield Stress [MPa]
Cortical Bone [27-31]	13,700	0.3	80
Cancellous bone [27]	1.370	0.3	---
Dentin [27]	18,600	0.31	---
Titanium Alloy [28-32]	110,000	0.3	830
Cobalt-chromium alloy [29]	220,000	0.3	720

Table 2. Muscular forces (N) assigned to the masticatory muscles for five different clenching tasks.

Muscle	ICP		LGF		LGF+B		INC		RMOL	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Superficial Masseter	190.4	190.4	51.4	34.3	49.5	22.8	76.2	76.2	137.1	114.2
Deep Masseter	81.6	81.6	21.2	29.4	21.2	29.4	21.2	21.2	58.7	48.9
Medial Pterugoid	132.8	132.8	132.8	12.2	127.6	15.7	136.3	136.3	146.8	104.9
Anterior Temporalis	154.8	154.8	11	104.3	36.3	85.3	12.6	12.6	115.3	91.6
Middle Temporalis	91.8	91.8	5.7	61.2	11.5	54.5	5.7	5.7	63.1	64
Posterior Temporalis	71.1	71.1	4.5	46.9	6	44.6	3	3	44.6	29.5
Inferior Lateral Pterugoid	18.1	18.1	9.4	39.5	---	---	47.5	47.5	20.1	43.5
Superior Lateral Pterugoid	16.9	16.9	2.3	5.7	---	---	14.3	14.3	---	---
Anterior Digastric	11.2	11.2	15.2	20.4	---	---	20	20	---	---

3. RESULTS AND DISCUSSION

3.1. Maximum Von Mises stress

There are various factors affecting the success of TMJ replacement, one of which is the level of stress generated during physiological activities. Fig. 2 shows the maximum von Mises stress generated for the two different materials under five different clenching loads. The highest amount of maximum von Mises stress was observed for the Ti-6Al-4V and CoCrMo alloy under the RMOL task at 343MPa and 363MPa, respectively. The LGF+B task produced the lowest magnitude of stress – 157MPa for Ti-6Al-4V and 212MPa for CoCrMo alloy. The maximum von Mises stress for all conditions were considerably lower than the yield strength of the respective materials. However, the maximum von Mises stresses for the Ti-6Al-4V implant in all five clenching tasks were less than those made of CoCrMo alloy. Coupled with a relatively high density of CoCrMo, it is therefore more plausible to use implant made of Ti-6Al-4V for TMJ implant.

3.2. Safety Factor

The safety factor (SF) must be considered in the design analysis as it describes how much a component can withstand the expected applied loads. It is often calculated based on the yield strength over the design stress where a value of 1 indicates that the applied load has reached the material limit. Fig. 3 shows the SF of the implant for all clenching tasks. The lowest SF value was 2 for CoCrMo alloy in RMOL task, and the highest SF was 5.3 for Ti-6Al-4V in LGF+B task. Again, implant made of Ti-6Al-4V was safer than its CoCrMo counterpart.

3.3. Mechanical adaptation

All implants designed to be used as a reinforced structure to the skeletal body should have similar mechanical properties to bone for proper adaptation. Fig. 4 shows the elastic region of Ti-6Al-4V, CoCrMo and cortical bone where the area under the elastic region is known as the elastic energy. The cortical bone has the lowest elastic modulus with a stiffness of at least eight times less than Ti-6Al-4V, and sixteen times less than CoCrMo. Ti-6Al-4V has an elastic modulus 50% lower than CoCrMo alloy, but higher yield strength by up to 13%. These two characteristics made Ti-6Al-4V a better choice as far as bone adaptation is concern. The relatively higher flexibility of Ti-6Al-4V is important as it can deform relatively more than CoCrMo under physiological loads, reducing the problem related to stiffness mismatch, possible bone fracture, and the potential failure due to bone resorption.

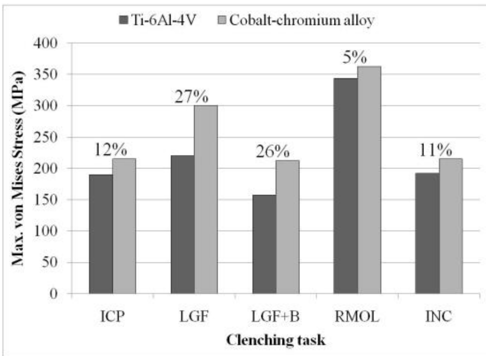

Fig. 2. Max Von Mises stress of the TMJ implants (Ti-6Al-4V and CoCrMo) under five clenching tasks.

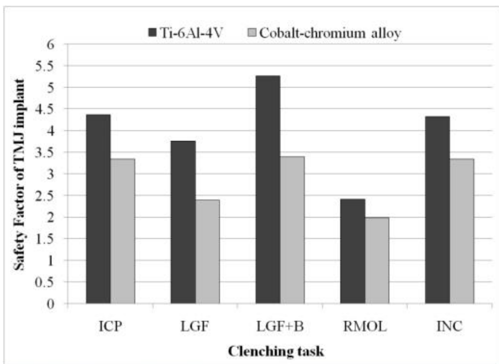

Fig. 3. Safety factor of the TMJ implants under five clenching tasks.

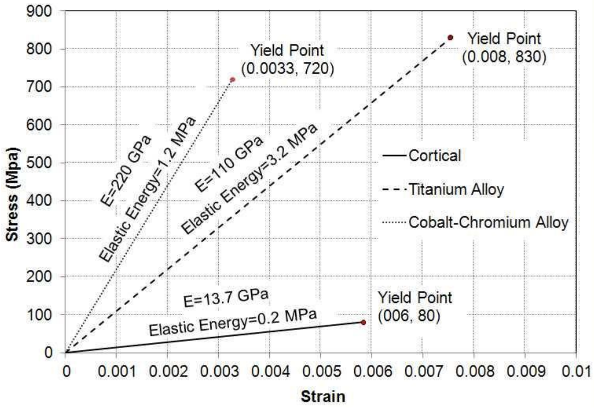

Fig. 4. The elastic regions of the cortical bone, Ti-6Al-4V and CoCrMo, and their respective elastic energies.

5. CONCLUSION

Two different TMJ implant materials were analysed under five simulated clenching tasks via finite element method. The results showed that the yield strengths of respective materials were not exceeded with a minimum safety factor of 2 for CoCrMo. Ti-6Al-4V was found to be superior to CoCrMo as it produced a relatively higher safety factor and mechanically more adaptable due to its relatively lower stiffness value.

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