HIGH-CYCLE FATIGUE BEHAVIOR OF TEMPOROMANDIBULAR JOINT IMPLANT

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A thesis submitted in fulfillment
of the requirements for the award of the degree of
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My deepest appreciation goes to my beloved father Mohammadali Arabshahi, my beloved mother Kokab Talebi, my beloved partner Jamal, my loved sisters: Zari, Fereshteh, Fatemeh and Tahereh and my best friends for ever: Miad, Batool and Lili, for the enormous love, support, encouragement and sacrifice they had given to me.
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The Temporomandibular Joint (TMJ) is a unique joint in the body which has a frequency of motion up to 2000 times per day. There are many TMJ disorders which can disable the joint leading to implantation of TMJ implant. Long-term follow-up of patients with TMJ implant needs to be studied for the benefit of both patients and clinicians. During the jaw movement, TMJ is subjected to varying loads which could cause fatigue failure of TMJ implant at high loading cycles. Therefore, it is important to ensure that TMJ prosthesis is protected against fatigue failure which indicates its long-term success. The aim of this study is to examine the fatigue analysis of three TMJ implants made of titanium alloy, cobalt-chromium alloy and stainless steel 316L, using finite element method. A three-dimensional model of mandible consisting of cortical and cancellous bone was developed from computed tomography images. A basic TMJ implant and fixation screws were modeled using three-dimensional modeling software. Finite element analysis of implanted mandible was done by assigning forces simulating the masticatory muscles to represent five static biting tasks. The loading configurations consisted of nine principal masticatory muscles. The results of static analysis showed that the resultant equivalent stresses in TMJ implant did not exceed the respective material’s yield stress. The safety factor of all three materials was larger than 1, which indicates sufficient strength for the five simulated clenching tasks. The Fatigue analysis showed that all three materials will never fail under fatigue. Titanium showed the best performance as it has the higher safety factor to ensure long-term success of a TMJ implant.

ABSTRACT
ABSTRAK

# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td></td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td></td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td></td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td></td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td></td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td></td>
<td>xi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td></td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td></td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td></td>
<td>xv</td>
</tr>
</tbody>
</table>

1 INTRODUCTION 1

1.1 Background 1
1.2 Problem Statement 4
1.3 Research Objectives 5
1.4 Importance of Research 6
1.5 Research Scopes 7
1.6 Structure of Thesis 8

2 LITERATURE REVIEW 9

2.1 Introduction 9
2.2 Temporomandibular Joint 10

2.2.1 TMJ Anatomy 10
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.2</td>
<td>TMJ Disorders</td>
<td>15</td>
</tr>
<tr>
<td>2.2.3</td>
<td>Total TMJ Replacement System</td>
<td>15</td>
</tr>
<tr>
<td>2.2.4</td>
<td>Commercial TMJ systems</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>Finite Element Method</td>
<td>23</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Finite Element Method in Biomechanics</td>
<td>23</td>
</tr>
<tr>
<td>2.3.1.1</td>
<td>Mesh Element</td>
<td>24</td>
</tr>
<tr>
<td>2.3.1.2</td>
<td>Von Mises Yield</td>
<td>24</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Finite Element Method in TMJ</td>
<td>25</td>
</tr>
<tr>
<td>2.4</td>
<td>Fatigue Analysis</td>
<td>28</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Background Information</td>
<td>28</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Stress-Life Diagram (S-N Diagram)</td>
<td>28</td>
</tr>
<tr>
<td>2.4.3</td>
<td>Mean Stress Correction</td>
<td>30</td>
</tr>
<tr>
<td>2.5</td>
<td>Summary</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>MATERIALS &amp; METHODS</td>
<td>33</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>33</td>
</tr>
<tr>
<td>3.2</td>
<td>Mandible Geometry</td>
<td>34</td>
</tr>
<tr>
<td>3.2.1</td>
<td>CT scan</td>
<td>34</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Image processing</td>
<td>35</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Data processing</td>
<td>38</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Three dimensional modeling</td>
<td>38</td>
</tr>
<tr>
<td>3.3</td>
<td>Modeling of TMJ Implant</td>
<td>39</td>
</tr>
<tr>
<td>3.4</td>
<td>Modeling of Implanted Mandible</td>
<td>40</td>
</tr>
<tr>
<td>3.5</td>
<td>Finite Element Model</td>
<td>40</td>
</tr>
<tr>
<td>3.6</td>
<td>Validation</td>
<td>43</td>
</tr>
<tr>
<td>3.7</td>
<td>Material Properties</td>
<td>46</td>
</tr>
<tr>
<td>3.8</td>
<td>Loading Condition</td>
<td>48</td>
</tr>
<tr>
<td>3.8.1</td>
<td>Static Loading Condition</td>
<td>48</td>
</tr>
<tr>
<td>3.8.2</td>
<td>Fatigue Loading Condition</td>
<td>54</td>
</tr>
<tr>
<td>3.9</td>
<td>Static Analysis</td>
<td>55</td>
</tr>
</tbody>
</table>
REFERENCES  88
List of publications  106
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The summarized information about the FDA approved TMJ implants</td>
<td>22</td>
</tr>
<tr>
<td>3.1</td>
<td>Isotropic material properties assigned to the components in FEA models</td>
<td>47</td>
</tr>
<tr>
<td>3.2</td>
<td>Directions of unit vectors (i.e., direction cosines) of muscular forces and forces assigned to the masticatory muscles</td>
<td>51</td>
</tr>
<tr>
<td>3.3</td>
<td>Weighting. and scaling factors assigned to the masticatory muscles for live clenching tasks</td>
<td>52</td>
</tr>
<tr>
<td>5.1</td>
<td>Mechanical properties of three materials</td>
<td>78</td>
</tr>
<tr>
<td>FIGURE NO.</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.1</td>
<td>The Location of the TMJ in the skull</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Anatomy of Temporomandibular Joint</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Ligament and capsule attachments in the TMJ</td>
<td>12</td>
</tr>
<tr>
<td>2.3</td>
<td>Muscles of mastication: lateral pterygoid (A), the temporalis muscle (B), masseter muscle (C) and medial pterygoid (D)</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Christensen system, its components and application on TMJ</td>
<td>18</td>
</tr>
<tr>
<td>2.5</td>
<td>Concepts System, its components and application on TMJ</td>
<td>19</td>
</tr>
<tr>
<td>2.6</td>
<td>Lorenz System, its components and application on TMJ</td>
<td>20</td>
</tr>
<tr>
<td>2.7</td>
<td>The S-N curve</td>
<td>29</td>
</tr>
<tr>
<td>2.8</td>
<td>Fully-reversed loading</td>
<td>30</td>
</tr>
<tr>
<td>2.9</td>
<td>The line diagram based on Goodman, Gerber and Soderberg theories</td>
<td>31</td>
</tr>
<tr>
<td>3.1</td>
<td>(a) Before data processing of CT scan images, these images have been thresholded with HU above 700. There are still artifacts around the teeth and bone (b) After data processing of CT scan images. The artifacts have been removed.</td>
<td>36, 37</td>
</tr>
<tr>
<td>3.2</td>
<td>3D model of TMJ implant based on commercially available TMJ implant</td>
<td>39</td>
</tr>
<tr>
<td>3.3</td>
<td>Mesh convergence study curve in TMJ implant and fixation screws</td>
<td>41</td>
</tr>
<tr>
<td>3.4</td>
<td>Finite element model of implanted mandible which has been meshed with total number of 156,165 elements and 231,724 nodes</td>
<td>42</td>
</tr>
<tr>
<td>3.5</td>
<td>The FE model used to simulate the Ramos work</td>
<td>45</td>
</tr>
<tr>
<td>3.6</td>
<td>A group of parallel vectors on the right ramus simulating the</td>
<td>50</td>
</tr>
</tbody>
</table>
masseter muscle loads

3.7 Condylar poles which condyle can rotate around them 53

3.8 S-N curve of all materials used in this study 54

4.1 Micro strain resulted in our FE models for (a) incisive model, (b) canine model, and (c) molar model 59

4.2 Stress distribution on the TMJ implant under five different clenching tasks for (a) Ti-6Al-4V, (b) CoCrMo, and (c) SS316L 61

4.3 Maximum von Mises stress in TMJ implant made of Titanium Alloy, Cobalt-chromium alloy and SS316L under five clenching tasks 63

4.4 The safety factor of TMJ implant under five clenching tasks 65

4.5 The elastic regions of the cortical bone, Ti-6Al-4V, CoCrMo and SS316L 66

4.6 The elastic energies of the cortical bone, Ti-6Al-4V, CoCrMo and SS316L 67

4.7 Evaluation of implant damage using the Miner’s rule 68

4.8 Minimum safety factor for the TMJ implant made of three different materials under five clenching tasks 70

5.1 Micro strains resulted in our FE models and experimental work of Ramos for (a) incisive model, (b) canine model, and (c) molar model 74
### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMJ</td>
<td>Temporomandibular Joint</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>TMD</td>
<td>Temporomandibular joint Disorders</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>MPa</td>
<td>Megapascal</td>
</tr>
<tr>
<td>GPa</td>
<td>Gigapascal</td>
</tr>
<tr>
<td>FDA</td>
<td>Food and Drug Administration</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>STL</td>
<td>Surface Tessellation Language</td>
</tr>
<tr>
<td>N</td>
<td>Newton</td>
</tr>
<tr>
<td>S-N curve</td>
<td>Stress versus Number of cycles to failure curve</td>
</tr>
<tr>
<td>TIRR</td>
<td>TMJ Implant Registry and Repository</td>
</tr>
<tr>
<td>HU</td>
<td>Hounsfield Unit</td>
</tr>
<tr>
<td>IGES</td>
<td>Initial Graphics Exchange Specification</td>
</tr>
<tr>
<td>ICP</td>
<td>Intercuspal Position</td>
</tr>
<tr>
<td>LGF</td>
<td>Left Group Function</td>
</tr>
<tr>
<td>LGF+B</td>
<td>Left Group Function with a cross-arch Balancing contact on the second molar</td>
</tr>
<tr>
<td>INC</td>
<td>Incisal Clenching</td>
</tr>
<tr>
<td>SOF</td>
<td>Safety Of Factor</td>
</tr>
<tr>
<td>D</td>
<td>Damage</td>
</tr>
<tr>
<td>SF</td>
<td>Safety Factor</td>
</tr>
<tr>
<td>E</td>
<td>Elastic modulus</td>
</tr>
<tr>
<td>UTM</td>
<td>Universiti Teknologi Malaysia</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

° - Degree
% - Percentage
σ - Stress
CHAPTER 1

INTRODUCTION

1.1 Background

The temporomandibular joint (TMJ) refers to the area straight in front of the ear on either side of the head, working in unison. It is one of the most often used joints of the body [1-3] and connects the upper jaw (maxilla) to the lower jaw (mandible) [1]. There are a hinge and a sliding compartment within the TMJ [2] which allow the lower jaw to move throughout the functions, particularly in biting and chewing, talking, swallowing and yawning [1], as shown in Figure 1.1.

There are many diseases such as cancer, congenital malformation, trauma and osteochondritis [5-6], which can damage TMJ and cause temporomandibular joint disorders (TMD). The prevalence of TMD symptoms is up to 60 percent, in which the female represent a greater population rather than male (the ratio is about 3:1). The most common age of beginning is 20–40 years while the signs are declined with age [7-8].

For treatment of TMD, many traditional approaches have been proposed over the years [9-17]. However, in some cases, which are not responded to traditional conservative therapies, a surgical approach to the TMJ is required to treat TMDs [18-
23]. But the mechanistic concepts (on which classic gnathology is based) and the sight of surgical procedure (as the ultimate treatment option for many supposedly abnormal TMJ conditions like internal derangements) had been interfaced, directing to an over-use of surgery for treatment of TMD [24-25]. In result, a number of patients experienced surgery incorrectly without any indications [26]. This promoted clinical complications and created a set of anatomically compromised TMJ patients [27]. In this context, early experiences with alloplastic materials and prosthetic systems for TMJ rehabilitation were catastrophic [28-34], however, new TMJ prosthetic systems have been come into existence in recent years and used for treatment of patients who have earlier undergone multiple failed TMJ (non-surgical and surgical) therapies [5].

Figure 1.1  The location of the TMJ in the skull [35]
Since December 30, 1998; the United States food and drug administration (FDA) have been approved the products of three manufacturers of TMJ implants. The accepted TMJ prosthetic systems are as follow [4]:

- TMJ Concepts (TMJ Concepts Inc., Ventura, CA, USA) which the condylar part of this implant is made of medical grade of titanium alloy;
- Christensen (TMJ Implants Inc., Golden, CO, USA), which the condylar part of this implant is made of cobalt-Chromium Alloy;
- Biomet/Lorenz (Biomet/Lorenz, Warsaw, IN, USA), which the condylar part of this implant is made of cobalt-Chromium Alloy.

Despite the current available TMJ prosthesis systems, there is no universally accepted implant for replacement of the TMJ [36]. Unfortunately, there is still a lack of data for TMJ prosthesis indications for evaluating about their success and survival rates [2]. The field of alloplastic TMJ replacement is still demanding, and further research is needed to characterize the essential design features and biomechanical requirements of these prostheses [37]. Owing to the nature of the bone structures of this joint, design of prostheses is somehow complex and materials play a significant role in enhancing the long-term life of the artificial joint [38-40]. Previous study by Kashi et. al [41] recommended the concurrent efforts to evaluate currently available and new biomaterials/implants for their mechanical and biocompatibility properties for TMJ implants. As previously mentioned, the condylar part of different TMJ prosthesis systems listed above, was made of medical grade of titanium alloy and cobalt-chromium alloy [4]. According to the literature there is another biomaterial SS316 which has been used in other field of orthopedics such as hip [42-43] and knee [44-45]. In this research we considered two current available biomaterials including medical grade of titanium alloy and cobalt-Chromium Alloy and also SS316 which is a new material for the field of TMJ implants.
This evaluation gives us an understanding about the characteristics different materials specially the new material, SS316, for TMJ implant and whether it can be successful and biocompatible. Consequently it will be easier to draw conclusions about the indications of TMJ implants material selection.

1.2 Problem Statement

In the United States alone, more than 30 million people may be affected with TMJ disorders (TMD) [46]. In spite of the fact that a large number of people suffered from TMD, research on this mysterious joint received relatively little attention [47]. Further research is therefore essential to ensure that the implant design features fully met the biomechanical requirements of such a complex human joint.

A short-term investigation, follow-up to 1–9 years, on total alloplastic TMJ reconstructions come out with encouraging results [2]. However, several complications post-surgery have been reported in recent years related to placement of such implants [48-51]. On the other hand, the design and material used for the implants significantly affect the long-term success post-surgery [52]. The TMJ joint has a frequency of motion up to 2000 times per day with daily movements[2-3]. Forces applied to the implant due to psychological movements generate stresses which can cause fatigue failure of implant material after a huge number of load cycles. Therefore fatigue failure is another potential problem which determines the long-term success of the implants. Hence, a study related to the biomechanical/fatigue analysis of implant is strongly needed [37]. Fatigue behaviour of implants have been reported for hip arthroplasty [53], knee arthroplasty [54-55], and dental implants [56-57]. However, there were no reports of fatigue behaviour of TMJ implants and it is needed to be studied [37]. Therefore, this
study investigated the fatigue life of TMJ implant for three different medical grade materials subjected to various physiological loading conditions via finite element method (FEM).

1.3 Research Objectives

Temporomandibular joint is one of the most complex human joints and replacement of the diseased joint requires careful consideration. Long-term follow up patients with TMJ implant bring many advantages for patients as well as clinicians. The TMJ implant is subjected to stresses during the daily movement. After a huge number of cycles of consequent loading, the fatigue failure might be happened. Therefore it is important to be ensured that TMJ prosthesis is secured against fatigue failure which demonstrates the long-term success of the prosthesis. Besides that, concurrent attempts to evaluate the currently available and new implant materials for their mechanical and biocompatibility properties need to be pursued. Therefore, the overall aim of the proposed research is then to investigate Fatigue life of TMJ implant made of three different biomaterials under physiological movements. To do this, the objectives of this research can be derived as follow:

Objective1: To construct three dimensional model of a human lower jaw and design a basic TMJ implant.
Objective2: To perform static and fatigue analysis on the implanted lower jaw under physiological movements via finite element method.
1.4 Importance of Research

TMJ is one of the least studied fields, which has not been investigated by the medical practitioners. Unfortunately, for who are interested in TMJ, there has been no community where engineers, scientists and clinicians communicate [58]. This project is significant because it can definitely extend the field of TMJ research and make a connection between mechanical engineering and medical science.

Reconstructive surgery usually involves replacing or augmenting a prosthetic implant in the human body. In the case of load-bearing implants, such as orthopaedic or dental implants, a pre-clinical testing procedure is required to be ensured that implant is efficacious and safe [59]. Computational modelling method is a useful virtual/non-invasive engineering tool that provides biomedical engineers a better understanding of implant performance in vivo. These findings can help practitioners to accomplish high success rate of various biomedical implants [59-74]. Due to the complexity of TMJ replacement, several works have utilised FEM to analyse the TMJ joint itself [75-79]. However, there have been fewer studies investigating TMJ implants via FEM [37].

In spite of the large number of patients who are suffered from TMJ disorders [46], there is still lack of data regarding this mysterious joint [80]. Although previous studies on total alloplastic TMJ reconstructions revealed satisfying results [2], there have been reported related complications [48-51]. This study is important because it gives us a better insight regarding the biomechanics and performance of the TMJ implant.

One of the design requirements of TMJ implants is expected lifetime up to 20 years [81]. Even though a short-term study (1–9 years follow-up) on total alloplastic
TMJ reconstructions reported the satisfying results [2], further research for long-lasting TMJ implants is needed. Fatigue life is one of the parameters which can indicate the long-term success of the implants. Fatigue behavior of orthopedic implants, such as hip and knee, as well as dental implants has been investigated [53-57]. Nevertheless, there is no research about the fatigue life of TMJ implant [37].

1.5 Research Scopes

This study was performed based on computed tomography (CT) datasets of the lower jaw of an adult. CT datasets were utilized to reconstruct the three-dimensional (3D) model of mandible via image processing software. 3D models were then converted into a 3D modeling software by means of a data processing software package. In addition, a 3D model of a commercial TMJ implant was developed. This study simulated an implanted mandible and then the static and fatigue analysis of implanted mandible was executed to adequately investigate the biomechanical behavior of a TMJ implant. This computer simulation study was performed using the finite element method (FEM). This method has been extensively used in other fields of orthopedics such as the hip, knee and dental implants [53-55, 82-85], and has been accepted by medical researchers as one of the significant assistive tools in surgical planning and treatment [60-66]. Even though this method has been used for simulation of different human joints, the number of studies related to the TMJ is fewer [37].
1.6 Structure of Thesis

This thesis consists of six chapters discuss about the introduction, literature review, methodology, results, discussions, conclusions and recommendations for future studies. Chapter 1 explains the problem statement, objectives, importance of the study and the proposed scopes of the research. Chapter 2 presents the literature reviews on the TMJ anatomy and related issues, finite element analysis and a background on fatigue analysis. Research methodology and a validation study are described in Chapter 3. Results obtained were presented in Chapter 4, and the results are discussed in Chapter 5. Finally, the conclusions, limitations and recommendations for the future work have been included are presented in Chapter 6.
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Journal


