HIGH-CYCLE FATIGUE BEHAVIOR OF TEMPOROMANDIBULAR JOINT IMPLANT

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ABSTRACT

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.

ABSTRAK

Sendi temporomandibular (TMJ) adalah sendi unik di dalam badan yang mempunyai kekerapan pergerakan sehingga 2000 kali sehari. Terdapat banyak penyakit TMJ yang boleh melumpuhkan sendi dan seterusnya membawa kepada penggunaan implan TMJ. Tindakan susulan jangka panjang pesakit yang menggunakan implan TMJ perlu dikaji untuk manfaat pesakit dan doktor. Semasa pergerakan rahang, TMJ akan dipengaruhi oleh pelbagai beban yang boleh menyebabkan kegagalan lesu implan TMJ pada kitaran beban yang tinggi. Ia adalah penting untuk memastikan TMJ prostesis terhindar daripada kegagalan lesu untuk kejayaan jangka panjang. Tujuan kajian ini adalah untuk mengkaji analisis keletihan tiga TMJ implan yang diperbuat daripada aloi titanium, aloi cobalt-kromium dan keluli tahan karat 316L, dengan menggunakan kaedah unsur terhingga. Model tiga dimensi rahang orang dewasa dibina daripada imej imbasan tomografi yang terdiri daripada tulang padat dan berongga. Satu implan TMJ dan beberapa skru penetapan telah dimodelkan menggunakan perisian permodelan tiga dimensi. Analisis unsur terhingga rahang bawah yang diimplan dijalankan dengan memberi daya kepada otot mastikasi untuk mewakili lima tugas menggigit. Konfigurasi beban terdiri daripada sembilan otot utama mastikasi. Keputusan analisis statik menunjukkan paduan tekanan setara dalam implan TMJ untuk bahan tersebut tidak melebihi tekanan alah mereka. Faktor keselamatan implan untuk ketiga-tiga bahan adalah lebih tinggi dari 1, menunjukkan bahawa ianya selamat di gunakan untuk kelima-lima tugas mengetap. Keputusan analisis keletihan menunjukkan ketiga-tiga implan tidak mengalami kegagalan di bawah keadaan daya tersebut. Titanium didapati lebih baik kerana ia menghasilkan faktor keselamatan yang lebih tinggi bagi memastikan kejayaan jangka panjang implan TMJ.

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LIST OF ABBREVIATIONS

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

LIST OF SYMBOLS

^{o}	-	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 mechanicistic 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].

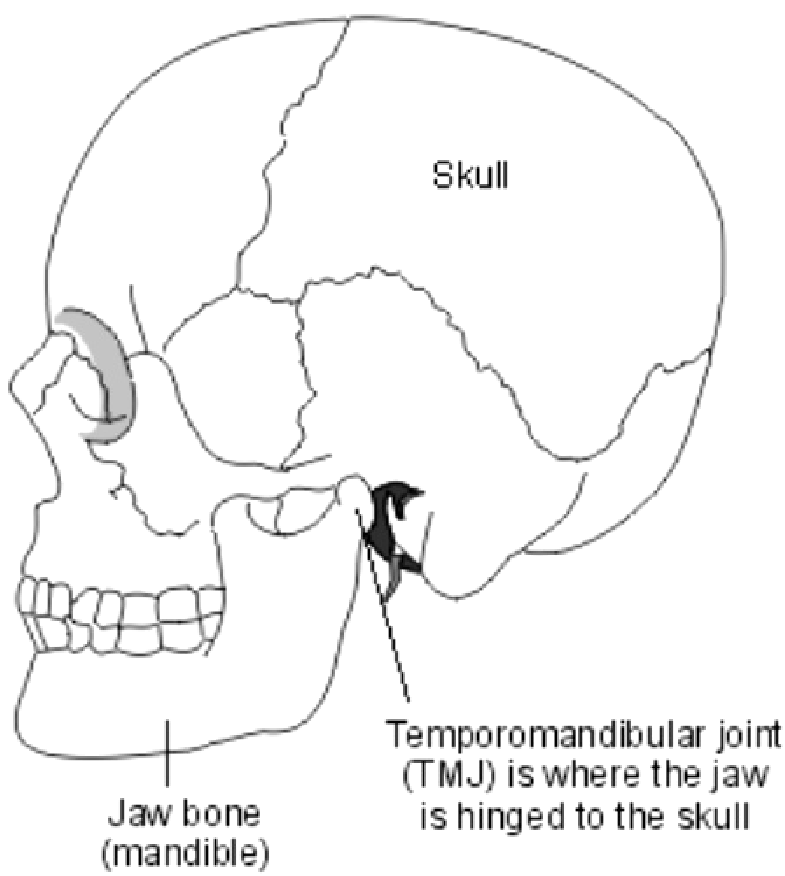

Figure 1.1 The location of the TMJ in the skull [35]

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 tree-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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List of publications

Journal

1. **Arabshahi, Z.**, M.R. Abdul Kadir, S.S.R. Koloor, and J. Kashani, *High cycle fatigue analysis of TMJ implant under five clenching tasks using finite element method.* Computer Methods in Biomechanics and Biomedical Engineering, 2012. Manuscript.
2. **Arabshahi, Z.**, J. Kashani, M. Abdul Kadir, and A. Azari, *Influence of the TMJ implant geometry on stress distribution.* Advanced Materials Research Journal, 2012. **488-489**: p. 991-995.
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5. **Arabshahi, Z.**, S.S.R. Koloor, J. Kashani, and M.R. Abdul Kadir, *Finite element analysis of TMJ implant under clenching loads.* Advanced Science Letters, 2012. **Accepted, In press**.