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Effects of bone remodelling process on evaluating biomechanical stability of implant-supported bridges

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Abstract

The study emphasizes the need to consider the bone remodelling process in stability analysis studies for implant-supported bridges. The research factors in the impact of changes in bone mechanical properties during the healing period, starting from implant placement until the completion of bone healing. The study demonstrates that bone remodelling is dynamic around the implant placement site, and the location of implant placement plays a crucial role in determining changes in bone density. Finite element analysis without considering bone remodelling results in the areas of high micro-strain and a relatively lower assessment of risk differences associated with the number of implants. This study provides valuable insight into the impact of considering bone remodelling on the stability analysis of implant-supported bridges. This can guide the development of better implant designs and treatment plans that take bone remodelling into account to improve patient outcomes.

Keywords: bone remodelling, dental implant, finite element analysis, implant-supported bridge, micro-strain, peri-implant bone stability.

1 Introduction

Due to the aging population, there has been an increasing interest in maintaining overall health throughout the lifespan. As a result, there has been a growing demand for improving oral function. Dental implant treatment is performed to replace missing teeth caused by oral diseases. While dental implants generally show high success rates, there are still anatomical and biomechanical limitations.

Factors affecting the success of dental implants include occlusal characteristics, implant design, and bone quality. Long-term follow-up studies on patients have reported complications such as loss of marginal bone and loss of osseointegration. Unlike natural teeth, implants lack periodontal ligaments, and stress is directly transmitted to the surrounding bone. Excessive stress can cause micro-cracks in the bone, which can negatively impact implant stability and lead to implant failure. In this respect, the process of bone remodelling is important.

Bone remodelling is a process where bones adapt to withstand load according to Wolff's law. It maintains mass variation by keeping mechanical strain within acceptable limits via a biomechanical feedback system as per Frost's Mechanostat theory. The difference between the minimum effective strain and the micro-strain initiates the bone remodelling process[1]. Previous studies have analysed bone remodelling of long bones using finite element analysis. Huiskes et al. applied adaptive bone remodelling aiming to maintain the constancy of the strain energy density[2]. Komarova et al. proposed a numerical model that predicts bone remodelling patterns based on changes in the bone cell population[3]. Bonfoh et al. applied a framework that applies mechanical loads to this numerical model to dental implants[4]. Reina et al. demonstrated that the principles of bone remodelling in long bones can be applied to predict bone density in the mandible[5].

This paper aimed to analyse the effect of the bone remodelling process on the evaluation of biomechanical stability by finite element analysis. The numerical model was implemented as a UMAT, user subroutine in the commercial finite element analysis software Abaqus. In the implant-supported bridge analysis, in order to confirm the difference according to whether or not the bone remodelling process was applied, 3 cases were composed according to the number of implants placed, and analyses were performed for each case by dividing bone remodelling applied/not applied.

2 Methods

2.1 Numerical model of bone remodelling

Bone remodelling, which involves absorption by osteoclasts and formation by osteoblasts, occurs in response to external loads throughout the lifespan. Komarova's proposed differential equation system is used in FE analysis to simulate this process, considering the mathematical model of autonomic and paracrine interactions between bone cells. The system calculates the mass variation of bones in each part, assigning evolved mechanical properties approximated from bone density.

Osteocytes detect mechanical stimuli from external loads and stimulate osteoclasts to initiate bone remodelling. Osteoblasts and osteoclasts interact with each other during bone formation and resorption. Mechanical stimuli are expressed as strain energy density $w(x_{GP})$ as shown in Equation (1). The strain energy density sensed at the position x_{GP} is written as Equation (2).

$$\Delta\Psi(x_{GP}) = C(n_O, \mu_i)\left(\frac{w(x_{GP})}{\rho} - W_0\right) \tag{1}$$

Bone cell populations at a bone remodelling region are described using two differential equations, shown in Equations (2) and (3). Variable g_{ij}, determined by Equations (4) and (5), was used to describe the effect of cell i on cell j and reflect effect of paracrine and autocrine. Autocrine effect is neglected since the bone cells were assumed to influence each other only.

$$\frac{dn_1}{dt} = \alpha_1 n_1^{g_{11}} n_2^{g_{21}} - \beta_1 n_1 \tag{2}$$

$$\frac{dn_2}{dt} = \alpha_2 n_1^{g_{12}} n_2^{g_{22}} - \beta_2 n_2 \tag{3}$$

$$g_{12} = A_1 + B_1 e^{-\gamma_1 \Delta\Psi^{GP}} \tag{4}$$

$$g_{21} = A_2 + B_2 e^{-\gamma_2 |\Delta\Psi^{GP}|} \tag{5}$$

The change in bone mass is calculated using the number of activated cells and their normalized activities. Bone density is calculated the identical formulation by assuming the isochoric process. The process described above was implemented as a user subroutine code of finite element analysis software ABAQUS.

2.2 Finite element analysis

This study used a three-dimensional bone model obtained via computed tomography (CT) from the human mandibular region, ranging from the first premolar to the second molar. The model was divided into two regions: cancellous bone and cortical bone, as shown in Figure 1. The peri-implant bone was separated into a cylindrical region to investigate its outcome. The study also divided the model into three groups based on the number and placement of implants. Group 1 had two implants placed in the PM1 and M2 positions, group 2 had three implants placed in the PM1, M1, and M2 positions, and group 3 had four implants placed in the PM1, PM2, M1, and M2 positions. Osstem Implant's complex, consisting of a crown, cement, abutment, screw, and fixture, was used for each implant.

The study outlines the three steps involved in conducting Finite Element (FE) analyses with and without considering the bone remodelling process. The preload step involves applying a load to the screw, approximating the compressive force generated by the turning force that tightens the screw. In the Bone remodelling step, an average masticatory force of 50 N over 150 days is applied perpendicular to the top of the crown unit. For the mastication step, a maximum mastication force of 200 N is applied at an angle of 30 degrees to the top of the crown unit. The FE analysis with the bone remodelling process considered simulates the preload, bone remodelling, and mastication steps. In contrast, the FE analysis without the bone remodelling process simulates only the preload and mastication steps. All interfaces are conditioned with a tie, and both sides of the bone segment are fixed in all directions.

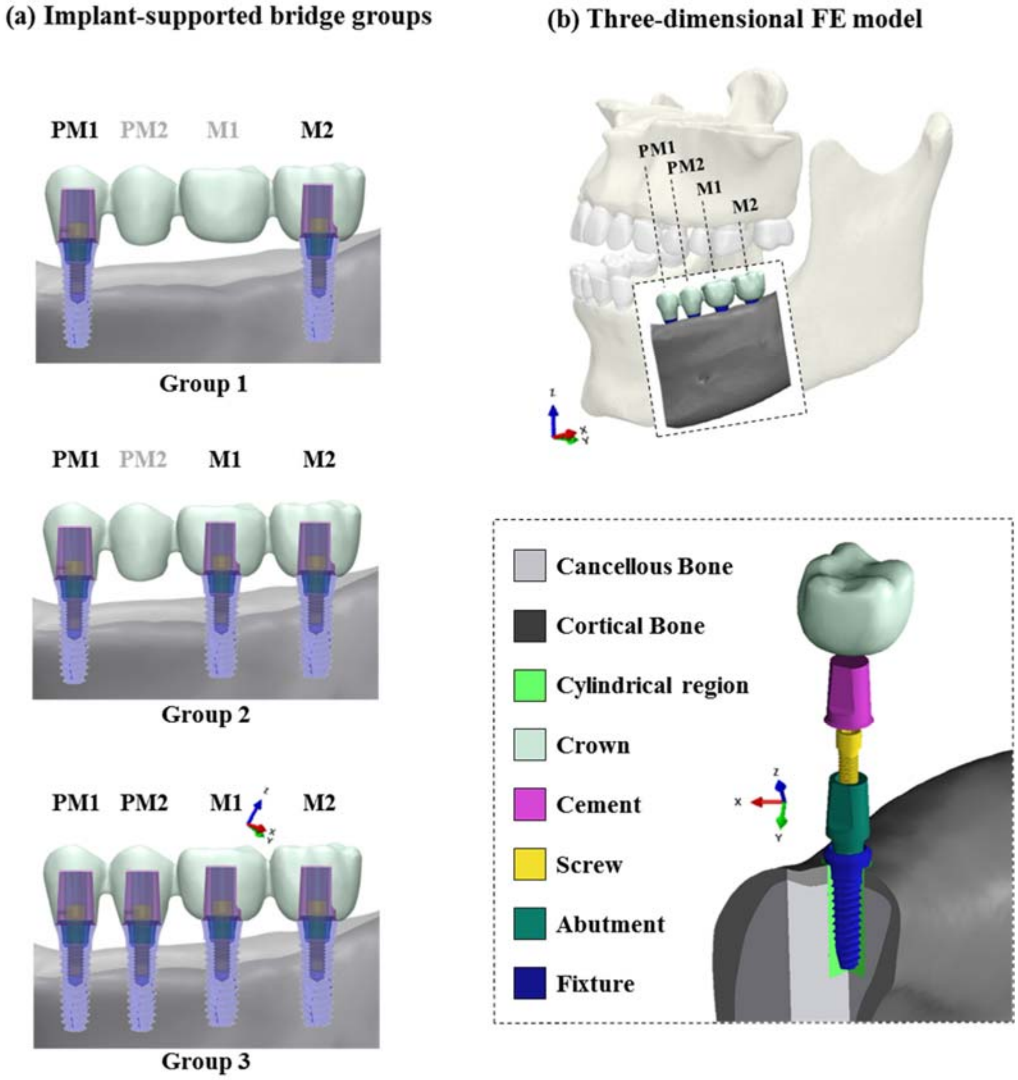


Figure 1 . (a) 3 groups according to the number of implants placed in bone (b) Finite element model of implant system and bone segment part; PM1: 1st Pre-molar, PM2: 2nd Pre-molar, M1: 1st molar, M2: 2nd molar

3 Results

In this study, the mechanical properties of the alveolar bone during the bone remodelling process were analysed using a numerical model proposed by Komarova. The density distribution of the cancellous bone on the last day of the bone remodelling process was compared by group and by implant placement position, as shown in

Figure 2. The average bone density changes around the implant at PM1 and M1 positions were recorded during the bone remodelling process. The results showed that the bone density around the implant significantly changes, especially around the implant placement site. The number and placement position of the implants had a significant impact on bone density, and the distribution of bone density was primarily affected by the implant placement position rather than the number of implants.

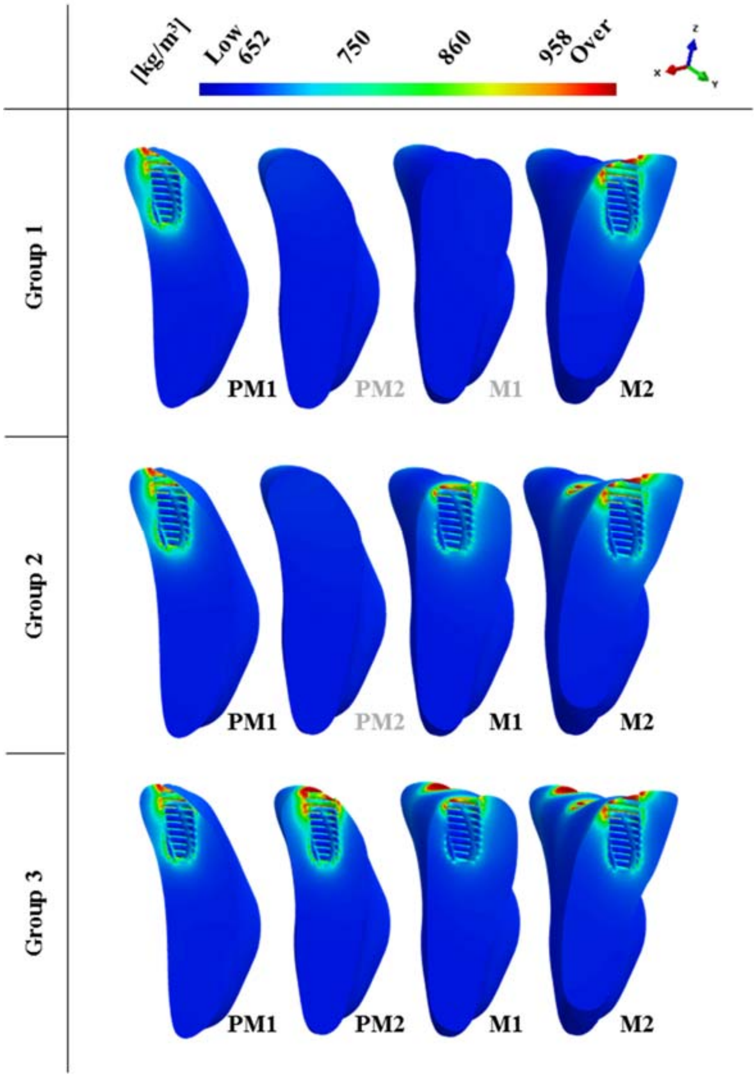
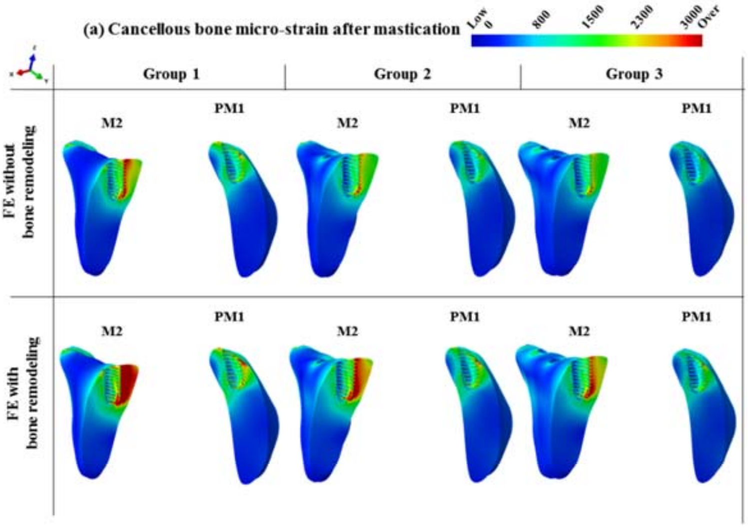


Figure 2 Distribution of density in cancellous bone after 150 day of bone remodelling process

Figure 3a describes the distribution of maximum principal strains occurring in the cancellous bone after the copyright stage. It was observed that the high strain concentration in the cancellous bone was located near the implant, in groups with fewer implants and in the M2 area of PM1. In terms of cross-sectional features, high strain concentration was observed around the neck of the implant in the PM1 area, and along the length of the implant in the M2 area. In all groups, the high strain distribution area in the analysis considering bone remodelling was wider than that in the analysis that did not consider bone remodelling. The difference between the high strain distribution areas in the analysis considering bone remodelling and the analysis that did not consider bone remodelling was greater with fewer implanted implants.


(a) Cancellous bone micro-strain after mastication

(b) Overstrain volume fraction

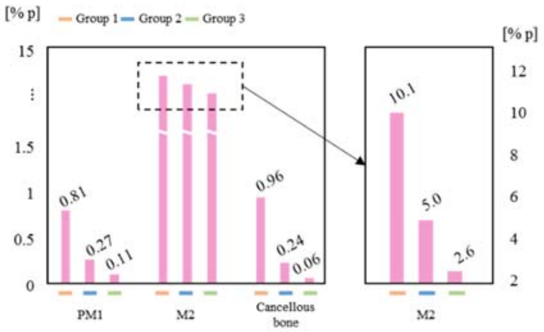


Figure 3 (a) Cancellous bone micro-strain (b) Volume fractions in which micro-strain extend 3000

Figure 3b displays the distribution of the maximum principal strain in cancellous bone after mastication. The volume fraction occupied by elements with a maximum principal strain exceeding 3000 micro-strain was calculated for the entire cancellous bone, the peri-implant bone in PM1 and M2 regions. The graph shows that the fatigue failure region increases as the number of implants decreases. Additionally, the volume fraction of the fatigue failure region considering the bone remodelling process was higher than that not considering it. The difference was more significant in the M2 region, and the smaller the number of implants, the greater the difference. The ratio of the fatigue failure area between the results with and without bone remodelling was higher in the M2 region. FE analysis with bone remodelling indicated a broader difference in the volume fraction of strain included in the fatigue failure range between groups.

4 Conclusions and Contributions

An FE analysis was performed to investigate the effect of the bone remodelling process on the stability of implant-supported bridges. Bone density changes during the bone remodelling period were analysed and the results of FE analysis considering the bone remodelling process were compared with those without considering it. The focus was on the effect of changes in bone mechanical properties during the bone remodelling process on the static analysis results. The results led to three main conclusions.

1. The results show that the location of implant placement has a more significant impact on bone density changes than the number of implants.
2. Not considering bone remodelling in FEA may lead to an underestimation of high strain distribution in cancellous bone, increasing the risk after implant placement.
3. Not considering bone remodelling underestimates the risk difference based on implant number, especially in the second molar position, where the difference in micro-strain and density changes is significant.

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