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A Novel Design to Optimize Biomechanical Properties of Dental Implant

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ABSTRACT

Objective: The main objective of this study is to evaluate a novel design to optimize dental implant biomechanics. According to this objective, evaluations of the resilient implant design which aimed to mimic biomechanical behaviors of natural tooth have been made and outcomes were compared with natural tooth and standard dental implants with using 3D hyper-elastic finite element analysis.

Methods: Models used in the study corresponding to conventional dental implant, natural tooth and resilient dental implant design. Hyper-elastic model analysis were performed for close presentment of mechanical behaviors of resilient materials like periodontal ligament and medical silicone. Top values of maximum principal stress, minimum principal stress of surrounding bone and displacement of each model were evaluated under axial and non-axial loading conditions with magnitude of 30N, 80N and 100N.

Results: Outcomes of finite element study showed reduction on maximum principal stress and minimum principal stress levels with the use of resilient dental implant comparing to the standard implant model. Standard implant model had been observed notably rigid in all loading conditions compared to the other models. Resilient implant model showed similar biomechanical characteristics with natural tooth model within the limitations of this study.

Conclusion: According to finite element analysis results; resilient implant design was able to resolve some biomechanical discrepancies and seem to have adequate biomechanical similarity with natural tooth under both axial and non-axial loading conditions.

Keywords: Resilient dental implant, dental implant biomechanics, tooth biomechanics, shock absorber, hyper elastic analysis

1. INTRODUCTION

Esthetically and functionally, replacement of missing organs, compatible with natural ones, is one of the main objectives of medicine and dentistry. In cases of replacement of missing teeth, dental implants seem to be fairly similar with natural teeth and bear many advantages and benefits compared to the other options. Nevertheless, there are some discrepancies with nature, especially in the field of biomechanics.

The biomechanical difference between a dental implant and a natural tooth is related to their attachment mechanisms. Healthy roots are normally covered with a specialized soft tissue called periodontal ligament, which makes connection between bone and root, provides biologic and biomechanical characteristics, such as shock absorption, force transmission, sensory and nutrition functions (1). On the other hand, a dental implant, which can be considered as a root analogue, makes rigid connection with bone via a mechanism called "osseointegration"(2). Although osseointegration with bone is a fundamental criterion of success in dental implantology, it creates the basis of the biomechanical differences with natural teeth.

Biomechanical disadvantages of dental implants are shown to be responsible for many undesirable situations, like microfractures and resorption of alveolar bone, loss of osseointegration, implant fracture, challenges in treatment planning of patients with partially edentulism. Additionally; current biomechanics of dental implants have been negatively affecting the healing period of immediate loaded implants (3).

The aim of this study is to evaluate a novel resilient dental implant modelling, mimicking biomechanical behavior of natural tooth. For this purpose, biomechanical comparison between natural tooth, conventional dental implant and resilient dental implant under axially and oblique loads have been conducted using finite element analysis (FEA).

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2. METHODS

2.1. 3D Models

A 3D section of phantom mandible without any malformation was derived from a computerized tomography in .stl data. The solid geometry of the mandible was reshaped from this data with a software: Mimics Innovation Suite (Materialise, Belgium). The surrounding cortical bone thickness was calibrated homogeneously as 2mm and cancellous bone dimensions were modelled 18mm width, 24,5mm depth and 20mm length. Conventional dental implant, natural tooth and resilient dental implant models are all embedded in the same bone structure.

2.1.1. Natural Tooth Model

Premolar (bicuspid) teeth with a single root was modelled with 14,5mm of root length and 8mm of crown height similar with average dimensions (4). Periodontal ligament tissue was modelled as 0,25mm width, homogeneously surrounding whole root surfaces (1). (Figure 1a,1b)

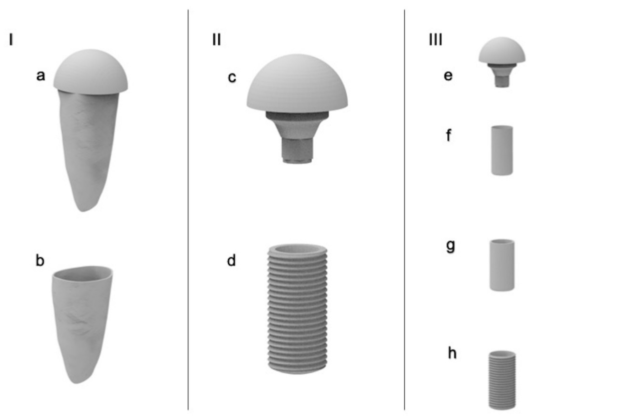

Figure 1. *I: Natural tooth model (a: root and hemisphere crown; b: periodontal ligament), II: Standard implant model (c: hemisphere crown and abutment, d: dental implant), III: Resilient implant model (e: hemisphere crown and abutment, f: internal titanium core, g: resilient layer, h: external titanium cylinder)*

2.1.2. Dental Implant Model

Cylindrical dental implant with symmetrical homogenous reverse buttress shaped grooves and dimensions of 4,8mm diameter and 10mm length was modelled. (Figure 1c,1d)

2.1.3. Resilient Implant Model

Morphologic features of the resilient implant were identical with the dental implant model. Micro motion and shock absorbing capacities of this design were planned to be provided by a resilient material, medical silicone, with thickness of 0,3mm that adopted homogeneously beneath the titanium surfaces, which are in direct contact with the bone. (Figure 1e,1f,g,h)

Coronal sections of the models were designed as a hemisphere with same dimensions and made of titanium for each model for standardization.

Modellings were transferred to a software; 3-matic (Materialise, Belgium), to create a three-dimensional mesh consisting mainly of tetrahedral nodes. All models assumed to be homogenous, linear elastic and isotropic; except for the periodontal ligament in tooth model and the medical silicone in resilient dental implant model. Hyper elastic model analysis were preferred for these materials.

Number of elements and nodes of each model were 74.261, 126.397 for standard implant model; 72.840, 127.919 for resilient implant model and 70,717, 114.377 for natural tooth model, respectively.

Mechanical properties of hyper elastic materials used in this study were C10: 0.04MPa, C01: 0.02MPa, d: 0.02 for PDL (5), C10: 0.14 MPa, C01:0.023MPa (6) for medical silicone. Mechanical properties of other elements used in this study are detailed in table1.

Table 1. *Material properties of finite element models.*

Component	Possion's ratio	Young modulus (MPa)
Titanium	0.35	110000
Dentin	0.31	18600
Cancellous bone	0.30	1370
Cortical bone	0.30	13700

2.2. Finite Element Analysis

Forces with magnitude of 30N,80N and 100N were applied on the most upper section of the hemisphere axially and non-axially with 45 degrees. Movement of the upper most section of each crown, maximum principal stresses and minimum principal stresses of surrounding peri implant bone were observed and compared between models. Since the models are created via a software and there has not been any material directly/indirectly gathered from an individual, approval of IRB was not found applicable.

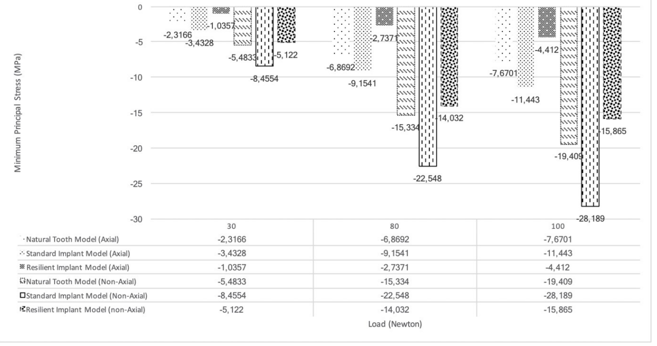

Figure 2. *Minimum principal stress of surrounding bone of each model, under 30N, 80N and 100N axial and non-axial loads presented in figure 2. Minimum principal stress of standard implant model concentrated at most coronal part of the bone with greater magnitudes.*

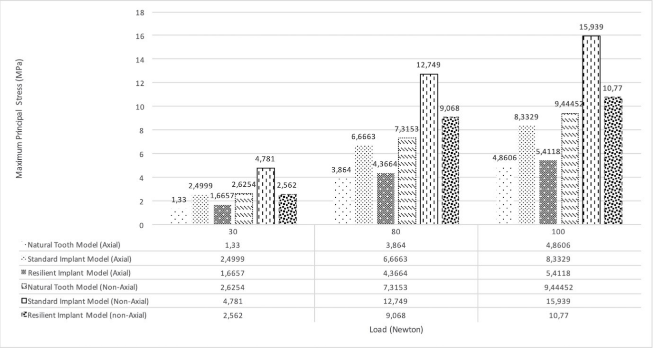

Figure 3. *Maximum principal stress of surrounding bone of each model under 30N, 80N and 100N axial and non-axial loads presented in figure 3. Maximum principal stress of standard implant model concentrated at most coronal part of the bone with greater magnitudes.*

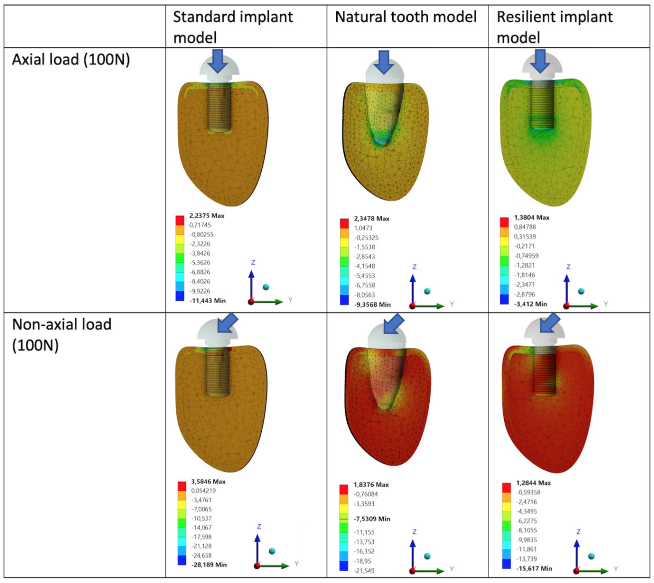

Figure 4. *Pattern of force transmission and accumulation area of minimum principal stresses on surrounding bone for each model under axial and non-axial load have been demonstrated in figure 4. Although amount of the stress had changed corresponding to the magnitude of applied forces, stress pattern remained same regardless from the amplitude of forces. The given color scales are specialized for each sample.*

3. RESULTS

For better traceability, the outcomes gathered from the finite element analysis of each model under axial and non-axial loads were summarized in figures. Models were compared in terms of vector and magnitude of applied forces. While, compared to the other models, maximum principal stress and minimum principal stress levels of standard implant model were observed to be higher and concentrated mostly around the superior part of the surrounding bone; resilient implant model and natural tooth model exhibited relatively similar stress distributions and magnitudes (Figure2-5).

Greater amount of displacement, higher maximum and minimum principal stresses were observed with non-axial loadings in all models. Natural tooth model and resilient implant model showed similar biomechanical behavior in all conditions. Higher levels of maximum principal stresses and minimum principal stresses were observed in standard implant model with both, axial and non-axial loading conditions. In resilient implant model and natural tooth model, the achieved maximum and minimum principal stress levels were similar and quite lower than standard implant model. Displacement of crown was also observed to be approximately similar in natural tooth model and resilient implant model. Moreover, these models showed a similar rate of increase in displacement correlated with increase in loading. On the other hand, standard implant model stayed notably rigid in all loading conditions.

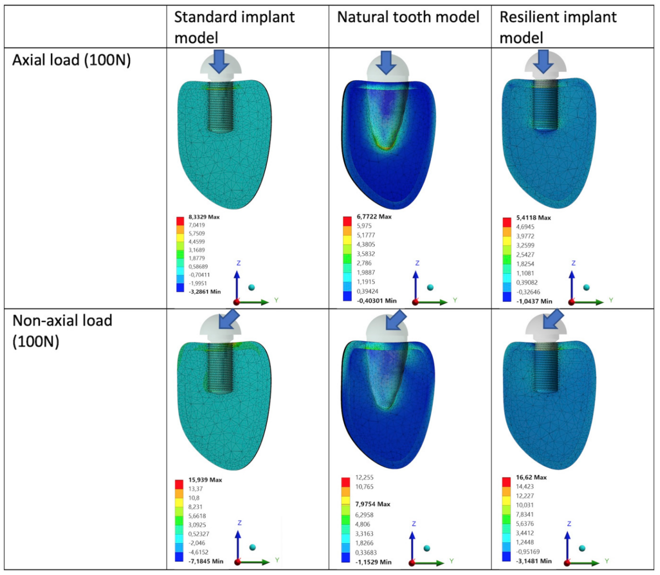

Figure 5. *Pattern of force transmission and accumulation area of maximum principal stresses on surrounding bone for each model under axial and non-axial load have been demonstrated in figure 5. Although amount of the stress had changed corresponding to the magnitude of applied forces, stress pattern remained same regardless from the amplitude of forces. The given color scales are specialized for each sample.*

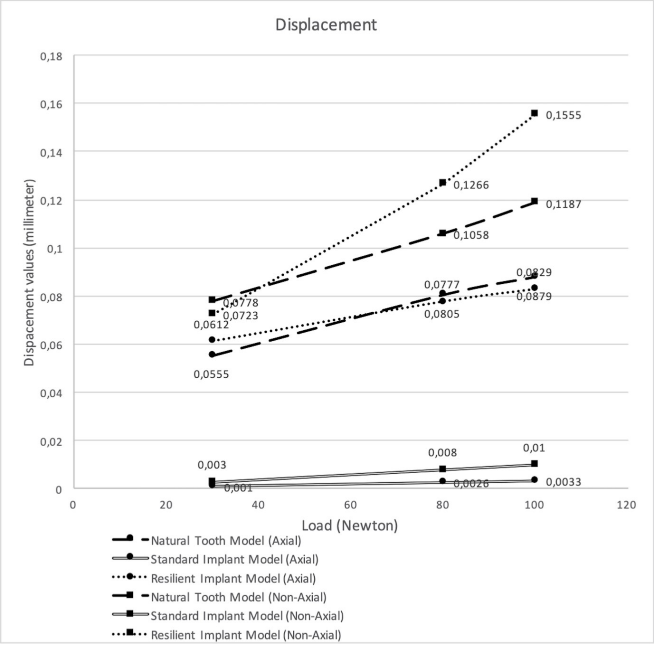

Figure 6. *Displacement values of the edge of each model is presented in the figure. Natural tooth model and resilient implant model showed relatively close micromovement patterns, whereas standard implant models were observed to be quite rigid under each circumstance.*

4. DISCUSSION

When it comes to rehabilitate tooth deficiencies, dental implants are the most popular treatment modality with high rate of success(7) . This popularity owes itself to many advantages such as transmitting occlusal forces, stimulating bone and preserving bone volume, achieving maximum bite force and chewing efficacy, working as a single unit, like natural teeth, if the prosthesis were designed separately from other teeth or implants (8). All in all, dental implants could be considered as an important contribution to dentistry.

Dental implants have taken the stage in the armamentarium of dentistry thanks to the mechanism called "osseointegration". Osseointegration is defined as "a direct structural and functional connection between ordered living bone and the surface of load-covering implant " (2) and is a master key for success. After an uneventful osseointegration period, implants act as a root analogue except for the inevitable rigid connection with bone. Unfortunately, this main success criteria, makes the basis of discrepancies with nature. Biomechanical discrepancies between tooth and dental implants are a result of the difference in attachment mechanisms; periodontal ligament and osseointegration. Beyond the role of attachment to the bone, PDL is responsible for micro-motion capability, absorption and distribution of forces.

The average amount of micro movement observed in natural teeth has been reported as 28-108 microns, and these values are shown as 3-5 microns in dental implants. (8). In addition to this, movement pattern of teeth can be observed in two phases. Non-linear and complicated initial movement occurs in PDL and after that a secondary movement occurs, as a result of elastic deformation of bone tissue. Dental implants are only capable of mimicking the secondary movement. A previous in-vivo study on measurement of tooth and implant mobility under physiological loadings also reported that, natural tooth has biphasic micromovement pattern which had ten-times greater magnitude compared to dental implants (9). Current data obtained from the standard implant model and the natural tooth model have shown significant consistency with previous studies in terms of the magnitude and behavior of the micro motion (9-11). Resilient implant model showed clear similarity with natural tooth model and previous data on biomechanics of natural teeth from other reports. Based on this similarity with the literature, it might be interpreted that, hyper-elastic model analysis also found as an effective method in accordance to intended use in both natural tooth and resilient implant model. Tooth to implant borne fixed prosthesis are also not desired because of this uncorrelated movement pattern, which has a hazardous effect on both implants and teeth. In some cases, these inharmonious two elements have been making the rehabilitations of patients more complicated, invasive and expensive.

Bone remodeling is related with mechanical inputs directed to the bone (12). It have been pointed out that the bone tissue continuously responds as apposition or resorption to the change in mechanical environment to maintain elastic deformation of bone (13). Dental implants transmit occlusal forces directly to the bone and stimulate and preserve the bone volume. Nevertheless, due to the rigid connection between bone and implant, the force is concentrated mostly on the coronal section of bone with higher levels and this situation has been reported as one of the reasons for bone resorption around dental implants (14, 15). On the other hand, PDL absorbs the forces and transmits homogeneously along the root surface, thereby bone resorption around healthy teeth are not commonly seen. In the present study the outcome of evaluation and comparison of dental implant model and standard implant model regarding the force concentration and transmission to the surrounding bone tissue were found to be similar with current literature (16-18). While relatively homogeneous force concentration on the bone tissue had been observed in natural tooth model, whole stresses were mostly concentrated on superior part of cortical bone around standard dental implant in all loading conditions. The difference of the amount of stresses on the surrounding bone have been became even more dramatic with non-axial forces. On the other hand, in all loading conditions, resilient implant model showed quite similar results with natural tooth model on behalf of force transmission and concentration. According to the outcome of this simulation, novel resilient implant design had been eliminated discrepancies on force transmission to and intense concentration points of the bone compared to the dental implant. In literature, the ultimate endurance of cortical bone tissue is shown to range from 72-26MPa in tension and 140-170 MPa in compression zones (19). In all loading conditions maximum and minimum principal stress values were monitored below the ultimate endurance levels of bone. Nevertheless, maximum values of tensional and compressional stresses have been encountered with standard implant model in all loading conditions compared to the natural tooth and resilient implant models. On the other hand, the results of the resilient implant model demonstrated the success of cushioning ability of the implant design by eliminating intense force transfer on the surrounding bone tissue. Still, regardless from the mechanical features as resilient or conventional implants, none of the implants have bear neural capacity like proprioception. Due to the lack of proprioception, dental implants have shown to experience higher loads compared to the natural tooth (8, 20). Even though resilient implants cannot eliminate neural oriented parafunctional habits, it may enhance the capacity of toleration.

Although it was not evaluated in this study, another potential advantage of resilient implant might be encountered in the healing period of immediate loaded implants. During the osseointegration period, micromovement of dental implant could affect bone healing adversely and lead to undesirable fibrous healing(3). In immediate loading protocols micromotion at bone-implant interface above 50-150 microns, was proposed to be avoided due to possible failure of osseointegration (21). In this case, resilient dental implant may affect bone healing by suspending and absorbing forces directed to the implant in immediate loading protocols.

Biomaterials, such as dental implants, are dynamic products; their designs and mechanical properties are constantly evolving in order to meet the increasing demands with the help of developing technology. There are and will be some studies and designs that aimed to optimize and enhance the biomechanical properties of dental implant, like currently evaluated design(11, 22-30). Of these, IMZ system had already been used clinically many years until they lost their popularity due to frequent complications (26). Regardless of previous failures and inconclusiveness, with the help of increased technology and enhanced biomaterials, several designs and prototypes, which are aimed the same goal with currently presented design, have recently being proposed to overcome standard implants' handicaps (11, 30).

In the presented design; external titanium cylinder, resilient area, internal core are planned to be analogues of dense bone, PDL and root respectively. External titanium cylinder and internal core are planned to be made of titanium that is already in use in dental implantology. While considering the resilient area; medical silicone, which is already being used in medicine and has been proven to be biocompatible was preferred as the resilient material (31). Main advantages of this design is that, all the materials used in the design were proven to be available in the armamentarium of medical materials and the materials are well known.

Main limitations of this study are mostly based on limitations of finite element analysis. Some assumptions and simplifications have been made with regard to material properties and model generations. Although living tissues had shown to be anisotropic and inhomogeneous, the structures modelled in this study were assumed to be homogenous, isotropic and linear elastic, except PDL and medical silicone, which are the main elements for this study(32) . In this study, implant models are assumed as fully osseointegrated, on the other hand histomorphometric studies have revealed that the bone implant contact never reaches 100% (33). Modelled section of the mandible was composed of cancellous bone, surrounded by 2mm thickness cortical bone layer homogeneously, which is also hard to observe in nature as well. Although, the forces applied in this study are shown to be in functional limits, then again, more hazardous loading conditions may occur especially in implants, which are incapable of proprioception (20). Finite element analysis cannot be evaluated statistically.

5. CONCLUSION

Within the limitations of this study, resilient dental implant model showed great biomechanical resemblance to natural tooth model. With the use of resilient dental implant, biomechanical discrepancies may be resolved and many advantages may be obtained. Therefore, development of dental implants mimicking mechanical behavior of natuæral tooth can be considered as a major advancement in implant dentistry. However, these outcomes were based on FEA and needs to be valideted by in vitro studies.

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Conflict of Interest:

The authors report no conflicts of interest

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