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FINITE ELEMENT ANALYSIS OF PERI-IMPLANT BONE BIOMECHANICS DUE TO CYCLIC LOADING

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ABSTRACT

Dental implants are subjected to repetitive masticatory loads throughout their service life. These cyclic loads generate stresses and strains in the peri-implant bone that may influence long-term implant success, particularly under varying degrees of osseointegration and bone quality. Clinical measurement of such biomechanical responses is challenging; therefore, finite element analysis (FEA) provides a suitable alternative. This study develops three-dimensional finite element models of mandibular peri-implant bone subjected to cyclic loading. Bone types II, III, and IV with 25%, 50%, 75%, and 100% osseointegration conditions were considered. Stress and strain distributions were evaluated, and fatigue life was estimated using mean-stress correction methods (Goodman, Gerber, and Smith–Watson–Topper). Results indicate that cyclic loading produces lower peak stresses than equivalent static loading and distributes stresses more uniformly along the peri-implant bone. Among the fatigue models, the Gerber method provided the most conservative and suitable life predictions. The proposed approach demonstrates the feasibility of cyclic loading simulation for peri-implant bone and provides insight into long-term biomechanical performance

KEYWORD

Finite element analysis, Dental implant, Molar teeth, Cyclic loading, Osseointegration, Fatigue life estimation

INTRODUCTION

Dental implants have been widely used since the early 1960s as replacements for missing or damaged teeth (Abraham, 2014). Functionally, implants transfer masticatory loads to the surrounding peri-implant bone in a manner similar to natural teeth (Kurniawan et al., 2012). Consequently, implants are subjected to millions of cyclic loading events during mastication over their expected long service life (>20 years), making fatigue behaviour a critical concern (Papavasiliou et al., 1997).

External loading induces stress and strain within the peri-implant bone, which governs implant success or failure. An average individual performs approximately 420 chewing cycles per meal, leading to more than 11 million cycles over an implant lifespan of about 25 years (Dahlberg, 1946; Papavasiliou et al., 1997). Despite this, limited finite element studies have addressed cyclic loading effects on jaw bone, and fatigue life estimation of peri-implant bone remains largely unexplored.

Papavasiliou et al. (1997) investigated stress distributions for implants with varying osseointegration levels (25–100%) and reported stress concentration in cortical bone near the crestal region. Similar findings were later confirmed by Kurniawan et al. (2012) using a refined transition-region modeling approach. Experimental and numerical studies by Duyck et al. (2001) demonstrated that cyclic loading generated high equivalent strains in marginal bone, exceeding interfacial strength, leading Isidor (2006) to conclude that cyclic loading can be more detrimental than static loading. In contrast, Menicucci et al. (2002) reported higher stresses under prolonged static loading due to time-dependent deformation effects, highlighting the lack of consensus in the literature.

Fatigue life assessment is commonly performed using either strain-based or mean-stress-based approaches. Although strain-based methods are generally more accurate, they require extensive experimental data and are difficult to implement in finite element-only studies (Roessle, 2000). Therefore, mean-stress-based fatigue models are more practical for numerical analysis. According to Gedeon (2014), these models are well suited for high-cycle fatigue conditions involving elastic stresses, as typically observed in bone–implant systems.

Given the limited and sometimes contradictory findings on cyclic loading of peri-implant bone, this study proposes a refined finite element approach incorporating a transition-region model and hysteresis-based cyclic loading. The objective is to evaluate stress and strain distributions in peri-implant bone under cyclic loading and to predict fatigue life under varying osseointegration conditions.

MATERIAL AND METHODOLOGY

Material Properties

The dental implant was modelled with an elastic modulus of 110 GPa and Poisson's ratio of 0.35, consistent with commonly used implant materials; titanium alloy (Papavasiliou et al., 1997; Duyck et al., 2001; Menicucci et al., 2002). The peri-implant bone was assumed to be isotropic for modelling simplicity, despite its known anisotropic nature (Kurniawan et al., 2012). Elastic properties were assigned to represent mandibular bone types II, III, and IV, incorporating both cortical and cancellous bone regions (Lekholm and Zarb, 1985).

A three-dimensional model of an edentulous posterior mandible with a single implant was developed based on established geometries from previous studies as shown in Figure 1 (O'Mahony et al., 2001; Petrie and Williams, 2005; Baggi et al., 2008; Pessoa et al., 2010). The implant was embedded 10 mm into the bone and assumed to be perfectly bonded to the surrounding bone, representing ideal osseointegration. Partial osseointegration conditions (25%, 50%, 75%, and 100%) were modelled using a transition region between the implant and bone. Adaptive meshing was employed to improve computational efficiency while maintaining accuracy. Fine mesh elements were concentrated in the peri-implant and transition regions, where stress gradients were expected to be highest, while coarser meshes were used elsewhere.

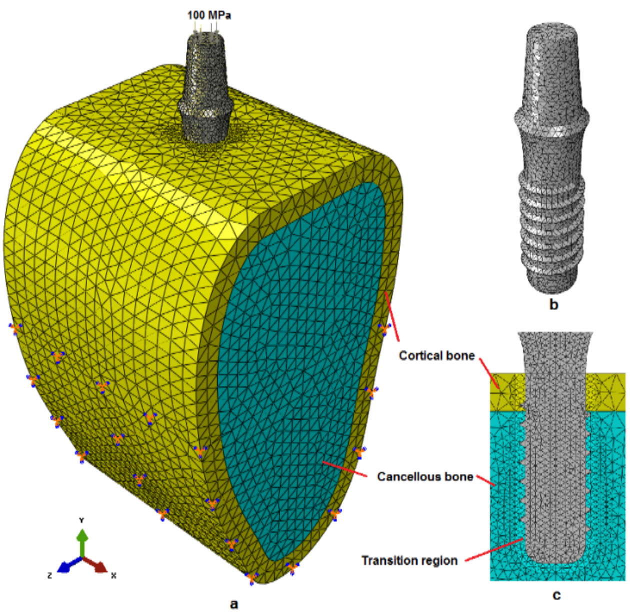

Figure 1: (a) The modelled bone with dental implant attached, shown with the applied load (P) and boundary conditions; (b) the prescribed dental implant and (c) transition region.

As mentioned by Pattin et al. (1996) and Hales. et al. (2002), in the case of unknown fatigue life of the model like dental implants, the load was repeatedly applied on the model for several cycles until the stabilize loop being obtained. In this case, a cyclic occlusal load with a peak magnitude equivalent to 100 MPa was applied to the implant crown until it stabilized which later used for stress, strain, and fatigue analyses.

Later, the resultant stress being used to predict the fatigue life using mean-stress effects approach. This approach contains equations given below had been used by Dowling et al. (2004) in previous works. There were 3 methods contains different effective alternating stress equation that being compared; Goodman, Gerber and Smith-Watson-Tapper (SWT) as listed in Table 1.

Table 1: Effective alternating stress equations

Method	Effective alternating stress ($\sigma_{ar} \approx \sigma_e$)		
	Goodman	Gerber	SWT
Equation	$\frac{\sigma_a}{\left(1-\frac{\sigma_m}{\sigma_u}\right)}$	$\frac{\sigma_a}{\left[1-\left(\frac{\sigma_m}{\sigma_u}\right)^2\right]}$	$\sqrt{\sigma_{max}\sigma_a}$

$$\sigma_{max} = \sigma_m + \sigma_a \quad (1)$$

$$\sigma_{min} = \sigma_m - \sigma_a \quad (2)$$

$$\sigma_a = \sigma_{max} - \sigma_{min}/2 \quad (3)$$

$$\sigma_m = \sigma_{max} + \sigma_{min}/2 \quad (4)$$

$$N = (\sigma_{ar}/a)^{1/b} \quad (5)$$

$$a = [0.9(\sigma_u)^2]/\sigma_e \quad (6)$$

$$b = -1/3 \log 0.9\, \sigma_u/\sigma_e \quad (7)$$

where,

σ_a = Alternating stress
$\sigma_{ar} \approx \sigma_e$ = Effective alternating stress
σ_m = Mean stress
N = Fatigue life cycles
σ_u = Ultimate tensile stress

RESULT AND DISCUSSION

Stress and strain are in fact, a common factor that need to be analyzed when pressure or force involved in certain problems. Through the cyclic loading that had been simulated until the 8th cycle, the stress and strain distribution values were obtained and listed into Table 2. In accordance with the non-isotropic behaviour of bone, which accounts for stresses and strains in all directions, the stress refers to von Mises stress and the strain refers to equivalent strain which need to be calculated.

Table 2: Maximum stress and strain value induced at peri-implant bone and taken at same node

Bone type	Osseointegration (%)	Peri-implant bone				Same node			
		Max. stress (MPa)		Max. strain (%)		Max. stress (MPa)		Max. strain (%)	
		Cor.	Can.	Cor.	Can.	Cor.	Can.	Cor.	Can.
II	25	39.25	1.09	< 0.1	< 0.1	39.25	0.76	< 0.1	< 0.1
	50	54.46	0.99	< 0.1	< 0.1	42.91	0.76	< 0.1	< 0.1
	75	39.80	5.28	< 0.1	< 0.1	42.16	0.74	< 0.1	< 0.1
	100	48.42	1.27	< 0.1	< 0.1	48.42	1.27	< 0.1	< 0.1
III	25	39.25	5.31	< 0.1	< 0.1	39.25	5.31	< 0.1	< 0.1
	50	78.50	3.37	< 0.1	< 0.1	45.05	3.37	< 0.1	< 0.1
	75	35.30	2.72	0.3	< 0.1	48.52	2.72	<0.1	< 0.1
	100	52.00	10.43	< 0.1	< 0.1	52.00	10.43	< 0.1	< 0.1
IV	25	86.97	2.67	< 0.1	< 0.1	0.36	1.07	< 0.1	< 0.1
	50	78.50	2.78	< 0.1	< 0.1	0.33	1.09	< 0.1	< 0.1
	75	117.75	2.73	< 0.1	< 0.1	0.35	1.17	< 0.1	< 0.1
	100	157.00	2.94	< 0.1	< 0.1	157.00	2.94	< 0.1	< 0.1

The highest stresses for bone types II and III were observed at 50% osseointegration, with values of 54.46 MPa and 78.50 MPa, respectively, while bone type IV exhibited the maximum stress of 157.00 MPa at full (100%) osseointegration. Strain values were negligible and therefore not considered significant. The stress variation between minimum and maximum values was approximately 30% for bone type II, 55% for bone type III, and 50% for bone type IV, indicating greater sensitivity to osseointegration in lower-density bone.

Stress contour plots (Figure 2) show that cyclic loading produced a more distributed stress field along the peri-implant bone rather than a strong concentration at the crestal region. Although stress magnitudes varied substantially with osseointegration level, stresses were consistently concentrated in cortical bone, with minimal involvement of cancellous bone, which agrees with previous biomechanical findings.

Fatigue life predictions using Goodman, Gerber and SWT mean-stress models indicate high-cycle fatigue behaviour in all cases ($N > 10^4$). Goodman model predicted increasing fatigue life with higher osseointegration for bone types II and III but showed an opposite trend for bone type IV. The Gerber model yielded consistent and conservative life estimates across all bone types, while the SWT method produced irregularly high predictions for bone type IV at 75% osseointegration.

Unlike most previous studies that focused on cyclic loading of the implant body (Anitua et al., 2008; Choi et al., 2011), this work emphasizes the response of peri-implant bone. The resulting stress and strain values were notably lower than those reported under static loading by Kurniawan et al. (2012), confirming that cyclic loading promotes more effective stress redistribution. Under cyclic conditions, peak stress locations were spread along the cortical bone rather than being confined to the crestal region, in contrast to static loading cases.

To verify this behavior, stresses and strains were extracted at the same nodal locations used in static loading analysis. The same trend was observed, with higher stresses occurring at higher osseointegration levels, particularly at 100%. Nevertheless, cyclic loading resulted in a more favorable stress distribution, reducing localized stress concentrations.

Fatigue life assessment suggests that peri-implant bone generally experiences very-high-cycle fatigue behavior ($N > 10^6$), consistent with the long-term functional demands of dental implants (Ayllón et al., 2014). Among the evaluated models, the Gerber method is most suitable for peri-implant bone analysis due to its conservative predictions. Although estimated fatigue lives were shorter than the expected clinical lifespan, these values represent worst-case scenarios, as bone remodeling—neglected in this model—would likely enhance long-term load-bearing capacity.

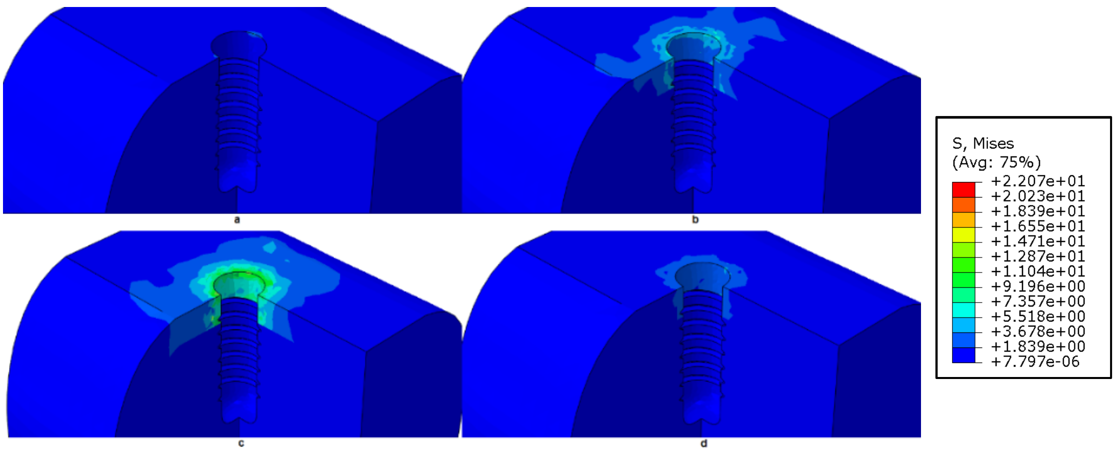

Figure 2: Stress distribution of bone type II at (a) 25%; (b) 50%; (c) 75%; and (d) 100%.

CONCLUSION

In conclusion, the cyclic loading approach that implement hysteresis loop as the working theory was proposed and its implementability was demonstrated. Cyclic loading does bring a major effect on the stress and strain distributions. Within the limitation of case study, bone type IV recorded the highest stress values regardless of its degree of osseointegration. In addition, mean-stress effects approach is suitable to be implemented in peri-implant bone analysis and Gerber method is the most applicable due to the results obtained.

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