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ORIGINAL ARTICLE

Biomechanical analysis of alveolar bone stress around implants with different thread designs and pitches in the mandibular molar area

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Abstract Threaded implants have been shown to play an important role in increasing mechanical osseointegration. The aim of this study was to determine bone stress distribution when using different types of implant thread pitches and designs. Five 3D finite element models were constructed to simulate bone stresses induced in implant bodies with two types of thread form: triangular ("Tri" prefix) and trapezoidal ("Trap" prefix). The former had thread pitches of 0.8, 1.2, and 1.6 mm, while the latter had thread pitches of 1.2 and 1.6 mm. A biting load of 143 N was applied vertically and obliquely to the occlusal central fossa of the crown. The main effects of each level of the three factors investigated (loading type, pitch, and thread form) in terms of the stress value were computed for all models. Results indicated that the loading type was the main factor of influence on the peak compressive stress of the alveolar bone. Optimal thread pitch was 1.2 mm for a triangular-thread implant, and a trapezoidal-threaded implant with thread pitch of 1.6 mm had the lowest stress value among trapezoidal-threaded implants. This study concluded that each thread form has its unique optimal thread pitch with regard to lower concentration of bone stress. Clinically, this study suggests that in biomechanical consideration, thread pitch exceeding 0.8 mm is more appropriate for a screwed implant. For clinical cases that require greater bone-implant interface, trapezoidal-threaded implants with thread pitch of 1.6 mm provide greater primary stability and lower concentration of bone stress under different loading directions.

Keywords Implant thread pitch and design · Finite element method · Stress distribution

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Introduction

Implant-supported fixed partial prostheses are being established as a treatment option for partially edentulous patients [1]. The principal function of implants is to provide stable support to the prosthesis after osseointegration with the jaw bone. Two types of interfacial fixation are necessary for successful stabilization of the implant-bone structure. The first is mechanical fixation by implant threads [2, 3]. This is the main contributing factor to the primary stability of the implant. The second type, which functions for long-term stabilization, is biological fixation. This fixation is necessary for further osseointegration of the inserted surfaces of the implant with the surrounding bone [4]. Many factors may influence this process, including implant shape, diameter, length, angulation [5, 6], surface treatment, bone quality, and surgical technique [7, 8]. Lin et al. found that the implant shape was an important determinant of stress distribution and has a more pronounced effect than implant length or diameter [9].

Many different implant designs are used in dental practice. These implants vary with regards to various features, such as thread or hollow cylindrical shape, and stepped implant type [10]. The threaded implant type has recently been widely applied. Thread designs include V-shape, square shape, buttress, reverse buttress shape, and spiral [11]. Threaded implants have been shown to play an important role in increasing mechanical osseointegration [2, 3] and influencing stress around implants during loading [12]. Huang et al. reported that "threaded implants could reduce both bone stress and the implant-bone sliding distance, thus potentially improving initial implant stability and long-term survival" [10]. Chun et al. indicated that a square thread shape with a small radius distributes stress more effectively [13]. By contrast, Eraslan and Inan found that thread designs did not affect the von Mises (EQV) concentration at supporting bone structures [14]. Previous studies have reported that the total contact area between the implant and bone plays a significant role in the osseointegration strength of implant-bone interface [8, 15], and this area is influenced by the implant surface treatment and implant thread pitch, depth, and width. Thread pitch refers to the distance from the center of the thread to the center of the next thread, measured parallel to the axis of a screw [11]. Thread depth is defined as the distance from the tip of the thread to the body. Thread width is the distance between the coronal and apical parts at the tip of a single thread in the same axial plane. Different thread shapes with the same pitch indicate that implant with different total contact areas at the implant-bone interface affects the primary stability. Previous research has revealed that stress loading of threaded implants is maximal at the interface between the first pitch of the implant and the cortical bone [16]. The thickness of the cortical bone ranges between 0.8 and 2.0 mm on average, with thicker bone having a higher load-bearing capacity [17–20]. Kong et al. emphasized that thread pitch exceeding 0.8 mm were optimal selection for a screwed implant by biomechanical consideration [21]. Interestingly, Lee et al. pointed out that square thread with a 0.6 mm pitch has optimal contact area and stress values [4]. Chung et al. found that implants with a pitch distance of 0.6 mm exhibited more crestal bone loss as compared to the implants with pitch distance of 0.5 mm [22]. The purpose of this study was to determine how to select the appropriate thread form and pitch to decrease stress concentration and enhance stability.

Finite element analysis (FEA) is important in cases when establishing the clinical conditions required to initiate a study with patients is very difficult. This study aimed to model the mandible with tomographic slices, which is currently a more realistic method of building a 3D model.

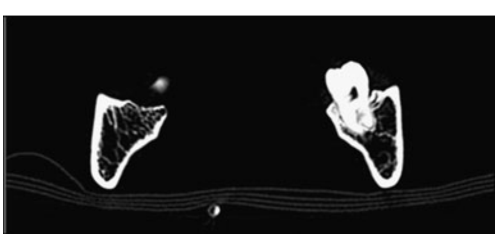

Fig. 1 Using computed tomography to scan the mandible and first molar area

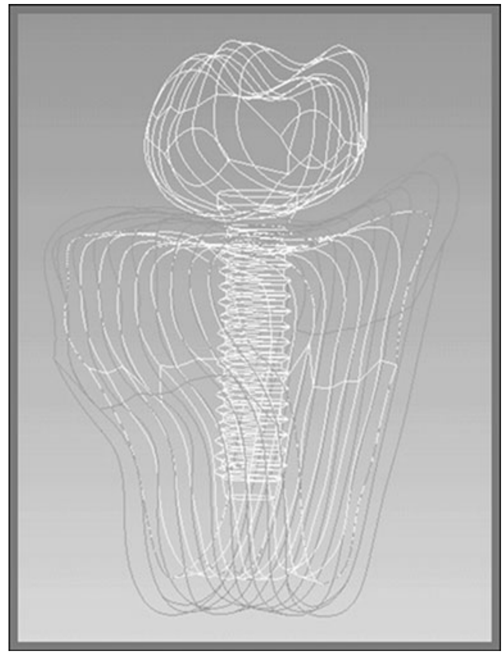

Fig. 2 Using computer-aided design (CAD) software to construct the model

However, the optimal stress values to use in calculations were not clear. Based on the research of Akça and Iplikçioğlu [23], von Mises stress (EQV) values were defined by the ductile material (such as metallic implants). For principal stress, a distinction is made between tensile and compressive stress. Positive values represent tensile stress, while negative values represent compressive stresses. The highest negative stress value (minimum principal stress) indicates the peak compressive stress. In general, compressive stress is more substantial than tensile stresses and provides reliable information for analyzing bone resorption [24]. Therefore, the maximum EQV values of the implant system and minimum principal stress (Pm) of bone were recorded for all models in this study.

This study hypothesized that the shorter pitch and triangular-thread form for implant bodies leads to higher

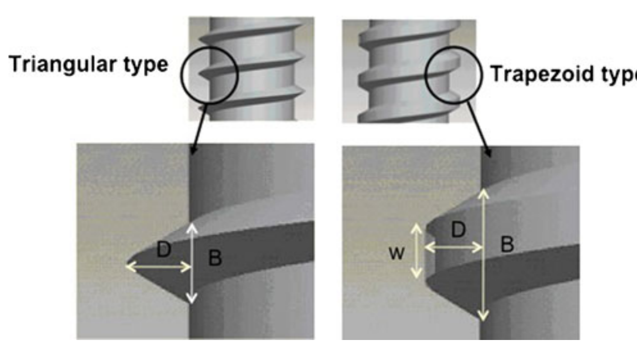

Fig. 3 Using CAD software to set up implant bodies with different thread designs. Constitutive parameters of implant threads including depth (*D*), width (*W*), and base (*B*)

Table 1 Material properties of the finite element models

Material	Young's modulus, E (MPa)	Poisson's ratio, ν	Shear modulus, G (MPa)
Cortical bone	Ex 12600	νxy 0.300	Gxy 4850
		νxz 0.253	
	Ey 12600	νxz 0.253	Gyz 5700
		νyx 0.300	
	Ez 19400	νzy 0.390	Gxz 5700
		νzx 0.390	
Cancellous bone	Ex 1148	νxy 0.055	Gxy 68
		νxz 0.010	
	Ey 210	νxz 0.322	Gyz 68
		νyx 0.010	
	Ez 1148	νzy 0.055	Gxz 434
		νzx 0.322	
Titanium	110000	0.35	
Porcelain	70000	0.19	

x, buccolingual; *y*, occluso-apical; *z*, mesiodistal

concentration of stress on the implant bodies and the alveolar bone around the implant. This study applied 3D FEA to investigate the stress distributions associated with triangular- and trapezoidal-threaded implants with different thread pitch to identify the main factors, which induce stress concentration.

Materials and methods

A series of computed tomography (CT) images from the mesial-to-distal sides of the first molar and bone area of a dry human mandible were obtained (Fig. 1). An ANSYS Workbench 10.0 (Swanson Analysis, Huston, PA, USA) was used to determine the key points in each CT image and to build a bone block. The implant models, which were constructed using a computer-aided design program (Pro/ENGINEER Wildfire 2.0, Parametric Technology Corporation, Needham, MA, USA), were 13-mm long and 3.75 mm in diameter (Fig. 2).

All implant bodies in this study were cylindrically shaped with symmetrical thread designs. All implant threads were V-shaped and divided into triangular or trapezoid thread form. Five finite element (FE) models comprising two thread designs (triangular and trapezoidal) and three thread pitches (0.8, 1.2, and 1.6 mm) were constructed in the posterior mandibular area (Fig. 3). The thread depth and base were 0.4 and 0.462 mm, respectively, for all triangular thread form implants. For all trapezoid thread form implants, thread depth was 0.4 mm, thread width was 0.462 mm, and thread base was 0.924 mm (Fig. 3).

All models were combined by Boolean operations using CAD software (Pro/ENGINEER). The triangular and trapezoidal thread designs are hereafter referred to as “Tri” and “Trap”, respectively with subscript suffixes indicating pitch (in millimeter). Due to limitations of model design, a $Trap_{0.8}$ model could not be constructed; hence, all comparisons were made using the $Tri_{0.8}$ model as the standard.

The material properties of the implant and prosthetic crown were assumed to be isotropic, while the cortical and trabecular bone were orthotropic (Table 1). Additionally, all materials were assumed to be homogeneous and linearly elastic [25]. The applied vertical and buccal oblique forces had a magnitude of 143 N [26–28], with the latter being set at 45° to the long axis of the implant on the central fossa. The lower border of the mandibular bone was constrained in the *x*, *y*, and *z* directions (zero displacement) as the boundary condition.

The outcome of an FE analysis is an approximate rather than an exact solution. Therefore, convergence testing was applied to the FE models to verify the mesh quality. The convergence criterion was change in minimum principal bone stress between elements with size change of less than 6%. The convergence testing indicated that elements with a size of 0.7 mm were sufficiently accurate for meshing of all FE models. To reduce the complexity of the results, the main effect of each level of the three investigated factors (loading type, pitch, and thread form) on mechanical response (stress) was computed based on statistical methods [19, 29], using JMP 6.0 (SAS Institute Inc., Crag, NC, USA) for analysis of variance (ANOVA). The analysis provided the

Table 2 The maximum von-Mises stress (EQV) of implant and the peak minimum principal stress (Pm) of the cortical bone around different implant designs

Implant	Implant-abutment complex EQV(Mpa)		Cortical bone Pm(-Mpa)		Cancellous bone(-Mpa)	
	Vertical	Oblique 45° B->L	Vertical	Oblique 45° B->L	Vertical	Oblique 45° B->L
$Tri_{0.8}$	119.8	1,057	86.2	226.1	4.84	24.98
$Tri_{1.2}$	137.1	309.4	83	188.6	4.04	21.21
$Tri_{1.6}$	155.8	574.1	83.8	269.4	4.19	22.42
$Trap_{1.2}$	118.1	262.5	103.3	197.6	4.36	19.02
$Trap_{1.6}$	117.5	324.6	81.1	138.4	3.6	21.32

B buccal; *L* lingual

Table 3 Summary of the analysis of variance (ANOVA) showed the statistical results of maximum stress with respect to bone

Source	DF	SS	MS	%TSS	*P* value
Loading type	1	67,907.86	67,907.86	96.14	*0.001
Pitch	2	0.017	0.0085	0	1.000
Thread form	1	2,724.84	2,724.84	3.86	0.132
Total	4	70,632.71		100	

DF, degrees of freedom; *SS*, sum of squares; *MS*, mean square; *TSS*, total sum of squares

percentage of the contribution of each investigated factor to the sum of squares (TSS), and was used to determine the factor levels that minimize the stress in the implant-bone system.

Results

Stress was concentrated on the thread area of the cervical part of the implant when forces were applied in various directions (Table 2). The peak EQV and Pm were higher for oblique loading than for vertical loading (Tables 3 and 4). Loading type had the most significant ($P<0.05$) effect on alveolar bone and implant body stress. The contribution percentages for loading type were 96.14% and 70.75% for the bone and implant, respectively. Thread pitch determined the magnitude of the stress, and the contribution percentage of pitch was 26.12% for the implant body ($P<0.05$). Thread form did not significantly affect stress distribution, whether in implant bodies or cortical bone area ($P>0.05$).

Peak stress was concentrated on the cortical area around the implant cervical area, especially at first pitch. When focusing on the cortical bone area in triangular-thread models, relative to the $Tri_{0.8}$ model, Pm was 3.7% and 2.8% lower in $Tri_{1.2}$ and $Tri_{1.6}$, respectively, during vertical loading (Table 2). In trapezoidal-thread models, relative to the $Trap_{1.2}$ model, Pm was 21.5% lower in $Trap_{1.6}$ during vertical loading. Comparison of the bony stress values of the five models under vertical loading showed that the bone stress of $Trap_{1.6}$ was the lowest, and the bone stress of $Trap_{1.2}$ was the highest (Figs. 4 and 5).

Under oblique 45° buccal-to-lingual loading (Table 2, Figs. 4 and 7), relative to model $Tri_{0.8}$, Pm was 16.5% lower in $Tri_{1.2}$ and 19.1% higher in $Tri_{1.6}$. Relative to the $Trap_{1.2}$ model, Pm was 30% lower in $Trap_{1.6}$. Comparison of the bony stress values of the five models under oblique 45° buccal-to-lingual loading showed that the bone stress of $Trap_{1.6}$ was the lowest, and the bone stress of $Tri_{1.6}$ was the highest.

Comparison of the different thread forms with the same pitch under vertical loading demonstrated that Pm was 24.5% higher in $Trap_{1.2}$ than in $Tri_{1.2}$, and 3.2% lower in $Trap_{1.6}$ than in $Tri_{1.6}$. Under oblique 45° buccal-to-lingual loading, Pm was 4.8% higher in $Trap_{1.2}$ than in $Tri_{1.2}$, and 48.6% lower in $Trap_{1.6}$ than in $Tri_{1.6}$.

When focusing on the implant-abutment complex, the peak stress was concentrated on the implant cervical area. Comparison of the triangular-thread models illustrated that $Tri_{0.8}$ had the lowest EQV values during vertical loading, but the highest EQV value during oblique loading (Table 2, Figs. 5, 6 and 7). Comparison of the trapezoidal-threaded models in this study showed that $Trap_{1.6}$ had the lower EQV values during vertical loading but higher values during oblique loading.

The minimum principal stress in cancellous bone under vertical loading was 7.9% higher in $Trap_{1.2}$ as compared to $Tri_{1.2}$, and 14% lower in $Trap_{1.6}$ as compared to $Tri_{1.6}$. Under oblique 45° buccal-to-lingual loading, minimum principal stress was 10.3% lower in $Trap_{1.2}$ than in $Tri_{1.2}$, and 4.9% lower in $Trap_{1.6}$ than in $Tri_{1.6}$.

Discussion

The findings of this study indicated that oblique loading and implant pitches are the main factors of influence on stress concentration in implant bodies. Oblique loading was the main factor of influence on stress distribution in cortical

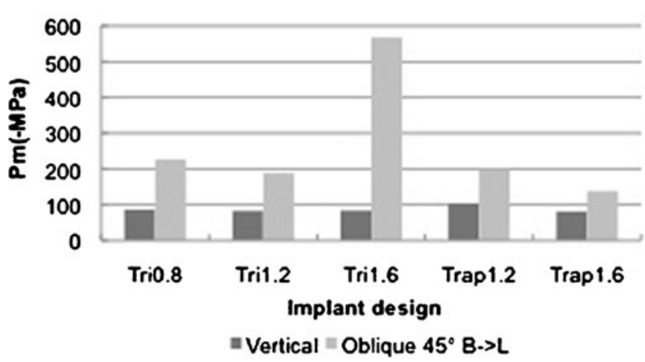

Fig. 4 Comparison of the minimum principal stress (*Pm*) in bone in implants of five designs

Table 4 Summary of the analysis of variance (ANOVA) showed the statistical results of maximum stress with respect to implant

Source	DF	SS	MS	%TSS	*P value*
Loading type	1	706,353.7	706,353.7	70.75	*0.0002
Pitch	2	260,705.6	130,352.8	26.12	*0.033
Thread form	1	31,275.9	31,275.9	3.13	0.3248
Total	4	998,335.2		100	

DF, degrees of freedom; *SS*, sum of squares; *MS*, mean square; *TSS*, total sum of squares

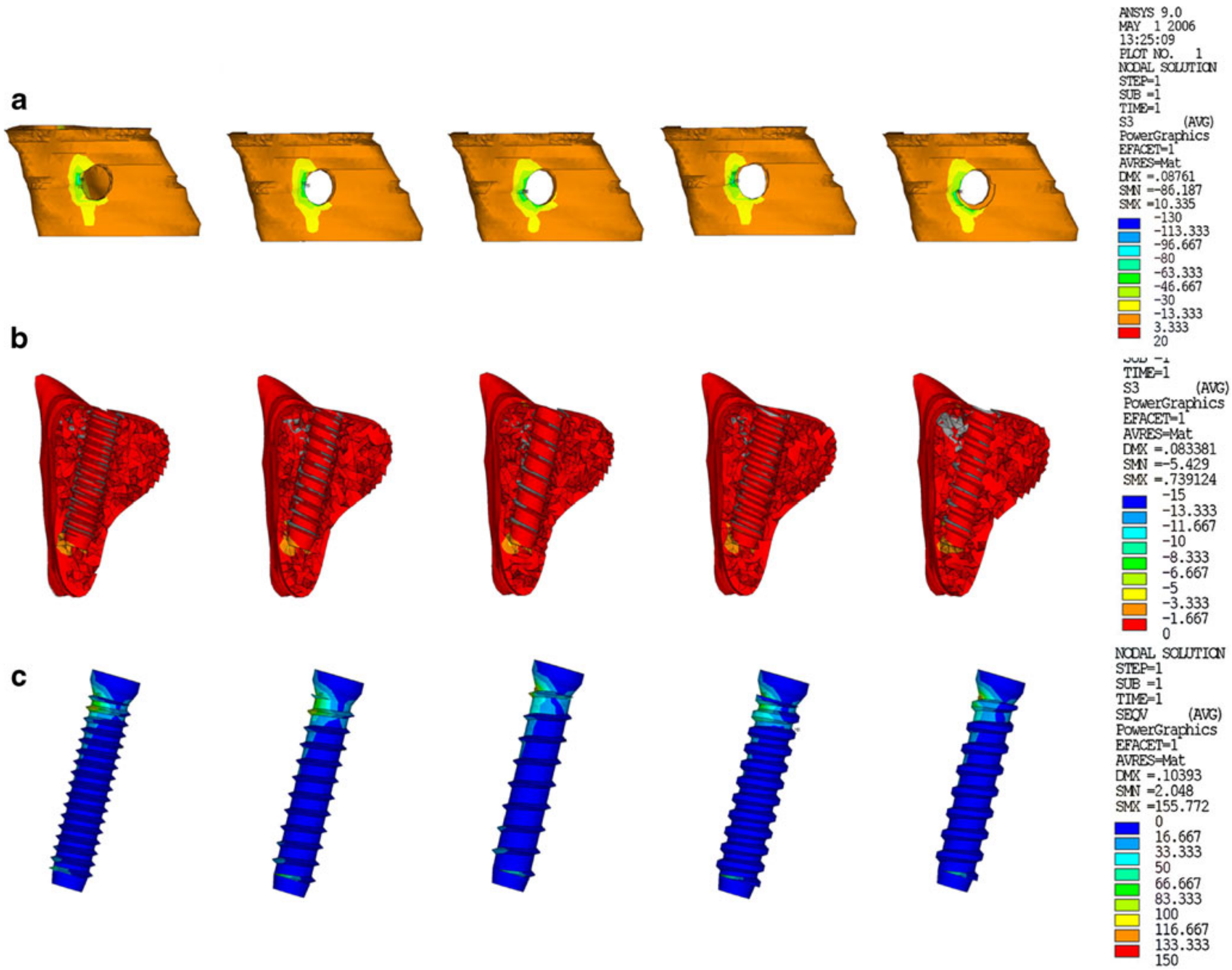

Fig. 5 Distributions of stresses in cortical bone (**a**), cancellous bone (**b**) and implant body (**c**) under vertical loading in five designs. From left to right are Tri $_{0.8}$, Tri $_{1.2}$, Tri $_{1.6}$, Trap $_{1.2}$, and Trap $_{1.6}$

bone around the implant. Although thread form (triangular or trapezoid) did not significantly influence stress distribution in the cortical bone area, selecting a more appropriate pitch design contributes to osseointegration in the same anatomic condition. In the immediate postoperative period, the initial stability of an inserted implant is a direct consequence of the geometric constraints imposed by the implant thread. In this study, the trapezoid-threaded implants had larger bone-implant interface, which is beneficial in primary stability. The 1.6-mm thread pitch implant design was optimal for lower concentration of bone stress. Additionally, this study suggests that in clinical application, thread pitch of 1.2 mm is more appropriate than thread pitches of 0.8 and 1.6 mm for triangular-thread form implants.

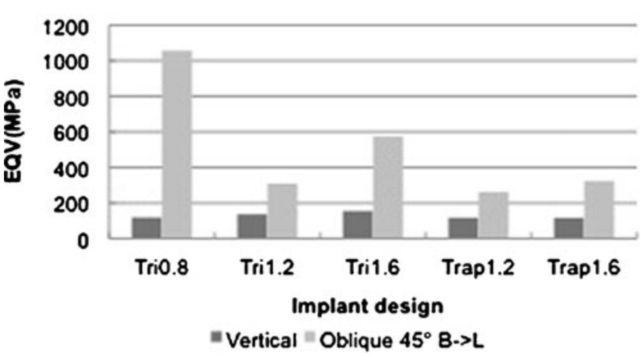

Fig. 6 Comparison of the maximum von Mises stress (*EQV*) in implants of five designs

Previous studies have found that regardless of whether force is vertical or oblique, peak stress is always concentrated on the cortical area around the implant cervical area, especially at the first pitch [12, 16]. Although implant fracture is a less frequent complication than bone destruction in the cervical area of the implant [30–32], the results of this study indicated that thread pitch significantly affects implant bodies. This study found that among the triangular-thread

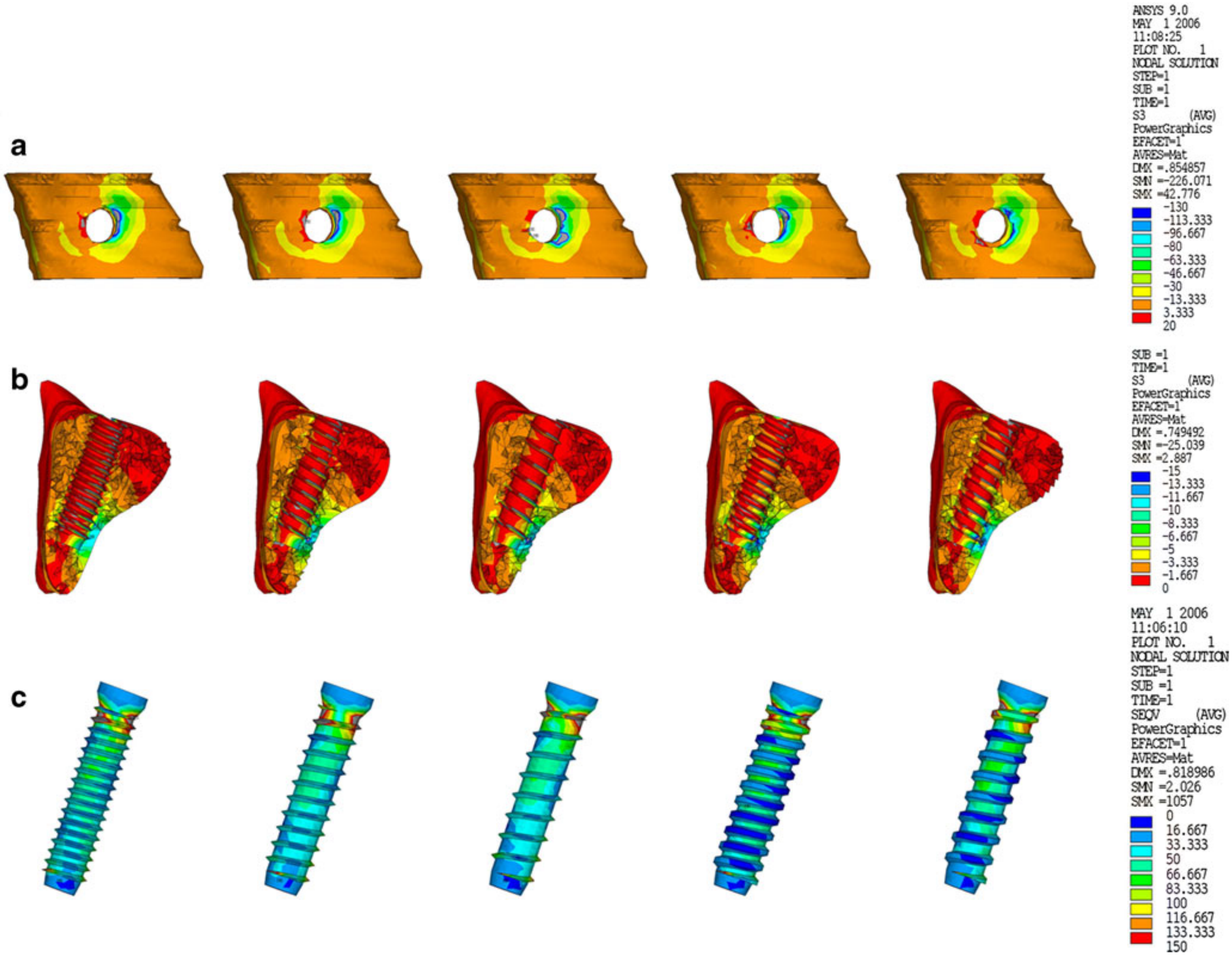

Fig. 7 Distribution of stresses in cortical bone (**a**), cancellous bone, (**b**) and the implant body (**c**) under oblique 45° buccal to lingual loading. From left to right are Tri $_{0.8}$, Tri $_{1.2}$, Tri $_{1.6}$, Trap $_{1.2}$, and Trap $_{1.6}$

implants, $\text{Tri}_{1.2}$ was associated with the lowest EQV stress during oblique loading. Among the trapezoid-thread implants, $\text{Trap}_{1.2}$ exhibited lower EQV stress than $\text{Trap}_{1.6}$.

Kong et al. emphasized that in biomechanical consideration, thread pitch exceeding 0.8 mm is optimal for a screwed implant [21]. This study showed similar findings. We suggest that thread pitch of 1.2 mm is more appropriate for triangular-thread form, while thread pitch of 1.6 mm is more appropriate for trapezoid-thread form. However, Lee et al. indicated that the square thread with a pitch of 0.6-mm pitch has optimal contact area and stress values [4]. This difference is due to different study designs, owing to the individual difference in cortical bone thickness. Although Eraslan et al. also suggested that using different thread form designs does not affect EQV at the supporting bone structure [14], no implant thread forms and pitches were used in the cortical bone area of their solid implant models. Previous researchers have indicated that stress distribution is affected by thread design around cancellous bone but not around cortical bone [13, 21, 33]. However, in our study, implant design did not significantly affect stress distribution in cancellous bone.

Not all of the trapezoidal-thread implants tested exhibited lower stress as compared to triangular-thread implants. Each type of thread has its optimal thread pitch with regard to lower concentration of bone stress. Although the $\text{Trap}_{1.6}$ showed the lowest concentration of bone stress under loading, it could lead to more insertion-induced resistance than triangular design during implant surgery. For clinical application, we suggest that dental surgeons carefully adhere to the selected implant system and surgical procedure to avoid the heat damage to the surrounding bone.

Conclusion

This study found that the loading type is the main factor of influence on stress distribution, and that in biomechanical consideration, thread pitch exceeding 0.8 mm are more appropriate for screwed implants. Each type of thread form has its optimal thread pitch with regard to lower concentration of bone stress. Optimal thread pitch for the triangular-thread form was 1.2 mm. For clinical cases which require greater bone-implant interface, a trapezoid-thread implant with a thread pitch of 1.6 mm thread pitch provides better primary stability and lower concentration of bone stress under different loading directions.

Conflict of interests The authors have no conflicts of interest to declare.

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