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RESEARCH

Stress distribution on the components of multi-unit abutment with different angulation under lateral force: a finite element analysis

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Abstract

Objectives Few studies have provided a detailed analysis of stress distribution on the components of multi-unit abutment (MUA)-implants complex, particularly the abutment screw and prosthetic screw, which are among the most fragile parts of the restoration. Our objective was to investigate the differences of stress distribution on the components of MUA-implants complex under varies loading conditions using finite element analysis.

Materials and methods We constructed MUA-implant complexes with different abutment angulations (0°, 17°, and 30°). A static force of 200 N was applied along the axis of the prosthetic abutment, accompanied by varying lateral forces (0 N, 30 N, and 100 N).

Results When subjected to a 200 N axial load, implants with a 30° angulated abutment experienced nearly 2.5 times the stress (1185 MPa) compared to straight abutments (437 MPa). The maximum stress of the straight MUA-implant was 8 times higher under a 100 N lateral force (2389 MPa) compared to that without lateral force. Prosthetic screws suffered higher stress concentration than the abutment screw and stress was mostly located near the first thread of the prosthetic screw.

Conclusions There is a distinct stress distribution pattern between the prosthetic screw and abutment screw, with the former experiencing higher stress concentration than the latter.

Clinical relevance The present study indicates that prosthetic screws are more vulnerable to mechanical complications and cautions should be raised to balance biting force to minimize the risks of mechanical complications in patients with angulated MUA-implants complex.

Keywords Finite element analysis · Multi-unit abutment · Prosthetic screw · Abutment screw · Stress distribution

Introduction

The preservation of bone quantity is crucial for the long-term functionality of dental implants [1]. Unlike natural teeth, which are supported by the periodontal ligament, osseointegrated dental implants exhibit lower resilience and shock absorption capacity [2, 3]. When subjected to loading, the stress applied on the dental implant is directly transmitted to the surrounding bone, leading to bone remodeling around peri-implant [4]. Consequently, uneven stress distribution of implant components can result in mechanical and biological complications of patients [5, 6].

For completely edentulous jaws, the 'All-on four' technique has gained widespread adoption among clinicians [7]. The "All-on-four" technique is based on screw-retained components, including straight and/or angulated multi-unit abutment (MUA) [8, 9]. The popularity of MUA in full arch implant restoration can be attributed to its ability to

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completely eliminate the need for cement and compensate the restoration's edge in cases of gingival height disparities, thus facilitating regular monitoring procedures [10, 11]. Additionally, the angulations of the MUA provide flexibility for patients with teeth misalignments or compromised jaw bone by offering 3–4 angle correction options [12]. However, compared with the cement-retained restoration, MUAs are more prone to mechanical failures, such as screw loosening or fracture, due to the lack of shock-absorbing cement [13].

Several studies have reported the influence of angulated abutments on mechanical stress. Liu et al. utilized finite element analysis (FEA) to compare stress distribution among abutment groups with 0°, 17°, and 30° angulations [14]. Their findings indicated that increased abutment angulation led to higher stress levels. In contrast, another FEA study examined stress distribution in abutments with 15°, 20°, 25°, and 30° angulations and reported no clear correlation between stress distribution and angulation [15]. Interestingly, this study found that the 20° angulated abutment exhibited lower stress levels compared to both the 15° and 30° angulated abutments. These conflicting results highlight the need for further research to clarify the relationship between abutment angulation and stress distribution.

There are essentially two pieces of screw components (an abutment screw and a relatively smaller prosthetic screw) to tighten the transmucosal MUA abutment and crown. Armentia et al. [16] observed that the prosthetic screw would be more vulnerable to mechanical problems, and Pjetursson et al. [17] reported a 10.8% abutment screw loosening rate after a 5-year follow-up. Notably, researchers have pointed out that the prosthetic screw of MUA is quite small, which further increases the risk of loosening or breakage [5]. However, few studies have specifically analyzed stress distribution of the abutment screw and prosthetic screw [18].

The masticatory forces induce axial forces and lateral force. Studies have highlighted the greater deterioration caused by the lateral force than axial forces [19, 20]. Richter et al. compared lateral and axial forces [21] and found that lateral force could generate higher stress on the bone-implant interface, particularly on the neck of the implant. Another study conducted by Cozzolino et al. also reported that lateral loads caused greater deformations of cortical bone than axial biting forces [22]. An animal study observed that the lateral force could disrupt the osseointegration, even in implants that had already achieved osseointegration [23]. Hence, understanding the stress pattern of the MUA under lateral force is critical to ensuring the long-term success of the implants and the restoration. However, there is scarce information available to determine the impact of lateral force on MUA with different angulations, let al.one the prosthetic and abutment screw.

To simulate the "All-on-Four" concept, which utilizes both straight and angulated (17° and 30°) multi-unit abutments (MUAs), we developed MUAs-implant complex with different angulations (0°, 17°, and 30°) using FEA [24]. FEA was chosen as the primary methodology because it allows for a detailed and controlled evaluation of stress distribution patterns under various loading conditions [6, 25, 26]. In this study, our objective was to investigate the differences in stress patterns among MUA with different angulations (0°, 17°, and 30°) using FEA. Additionally, we compared the stress distribution of each component of the MUA-implant complex (including the MUA, implant, abutment screw, and prosthetic screw) under a 200 N static force along the prosthetic abutment axis, with varying lateral forces (0 N, 30 N, and 100 N).

Methods

3D reconstruction of the mandibular bone

The study protocol was designed in compliance with the Helsinki Declaration and approved by the ethical committee of the School and Hospital of Stomatology, Fujian Medical University (No. 2022053). A computed tomography examination was performed on a 35-year-old healthy male volunteer with a healthy craniofacial structure and dentition after a medical history interview [27] and oral examination. Prior to participation, the volunteer provided informed consent. The computed tomography files were then imported to Materialise Mimics Innovation Suite software (Materialise, Belgium) and a section of the mandibular bone structure around the left first molar was mathematically filed. This model considered a cortical bone thickness of 2 mm surrounding the trabecular bone, simulating bone type II according to the Lekholm and Zarb classification [28].

Finite element model components and mesh generation

The geometric modeling of the MUA-implant complex was constructed based on the physical components and data provided by the manufacturer (Nobel Biocare, Gothenburg, Sweden). The complex consisted of a 4.3 mm × 10 mm NobelActive® implant, MUAs with a 3.5 mm collar height and various angulations (0°, 17°, and 30°), as well as the abutment screw, prosthetic screw, and prosthetic abutment. As demonstrated in previous studies, crown parameters, such as cusp inclination, occlusal contact distribution, contour, and material, significantly influence stress distribution around dental implants [6, 29, 30]. The crown was not simulated in this study to minimize the confounding factor of

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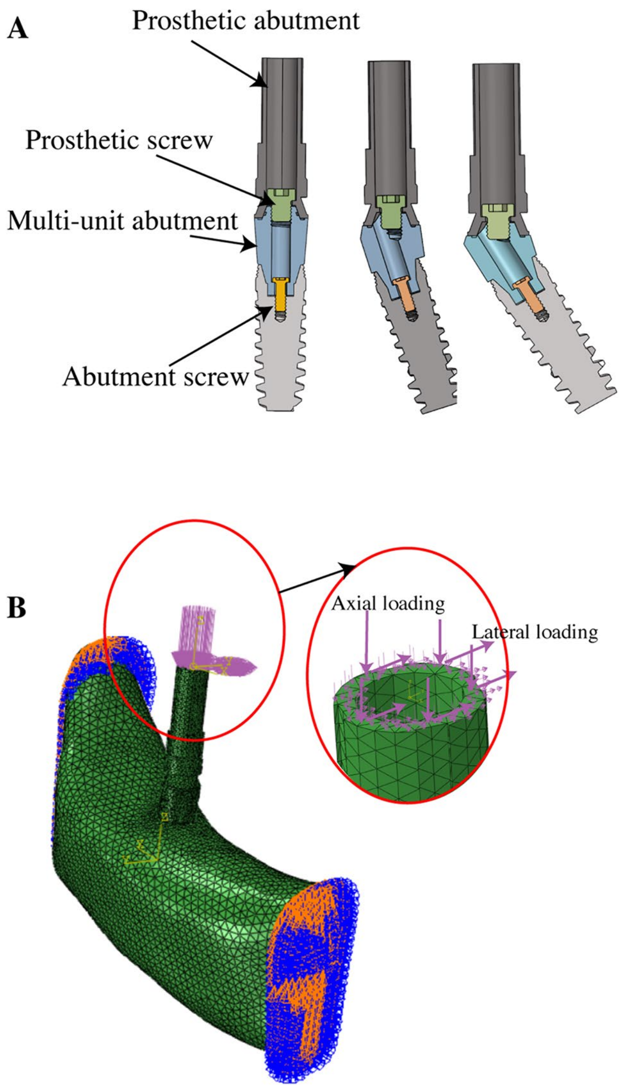

Fig. 1 The MUA-implant complex models with different abutment angulations (0°, 17°, and 30°). **A**, 3D model and detailed components of MUA- implant complex with different angulations. **B**, the axial and lateral loading applied on the meshed MUA-implant complex

Table 1 Young's modulus and Poisson's ratio of the materials material [31, 32]

Materials	Young's modulus (MPa)	Poisson's ratio
Cortical bone	13,700	0.3
Trabecular bone	1370	0.3
MUA-implant complex	103,400	0.35

crown designing. All components were meshed using computer-aided engineering software (SolidWorks Simulation, SolidWorks Corporation, USA), as shown in Fig. 1A. The Young's modulus and Poisson's ratio for cortical bone, cancellous bone, and the implant-MUA complex were determined from previous studies and are summarized in Table 1 [31, 32].

The geometric models are then imported into Hypermesh software ((Altair Engineering, USA)) for meshing and assembled. The individual components are discretized to generate 4-noded 6-degrees of freedom tetrahedral elements. The convergence criterion was defined as a change of less than 6% in the maximum von Mises stress in the bone between successive mesh refinements, based on previous study [33]. To simulate the osseointegrated implants, a "fixed bond" condition was set between the bone and implants. The interface between screw components (prosthetic screw and abutment) and the surrounding components was simulated with micro-sliding with a 0.5 friction coefficient, while the remaining interfaces were set as a contact condition. The finite element model of the implant with different multi-abutment units consisted of a total of 31,713−35,502 nodes and 132,996−155,375 elements, with 13,901/52,897 nodes/elements for the 0° MUA-implant complex, 12,944/48,843 for the 17° MUA-implant complex, and 12,516/46,821 for the 30° MUA-implant complex.

Boundary conditions

After the assembly, the models were exported to finite element software (ANSYS Workbench 15.0, Pennsylvania, USA) to perform the analysis through numeric calculus. A standard coordinate system was constructed with the x-axis as the mesial-distal direction along the bone segment, the y-axis as the labial-lingual direction perpendicular to the bone axis, and the z-axis as the superior-inferior direction along the prosthetic abutment axis. The mesial, lingual, and superior directions were defined as the + x, +y, and + z directions, respectively. Boundary conditions for all models were set as zero movement and rotation in all directions at the mesial and distal exterior surfaces of the bony segment.

Loading conditions

Axial and lateral forces were applied to the prosthetic abutment, as shown in Fig. 1B. With the purpose to explore the impact of the lateral force and axial force, the MUA-implant complex was exposed to 3 loading conditions: condition A (200 N axial force with 0 N lateral force), condition B (200 N axial force with 30 N lateral force) and condition C (200 N axial force with 100 N lateral force). To closely inspect the stress distribution of the abutment and prosthetic screw, the screw was visually divided into upper, middle, and bottom parts, and the corresponding stress was recorded.

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Results

Stress distribution of implants

The stress distribution of the implants with various MUA angulation under different loading conditions is exhibited in Fig. 2. It could be observed that no matter the loading conditions within this study, stress of implant was mostly distributed in the neck of implant.

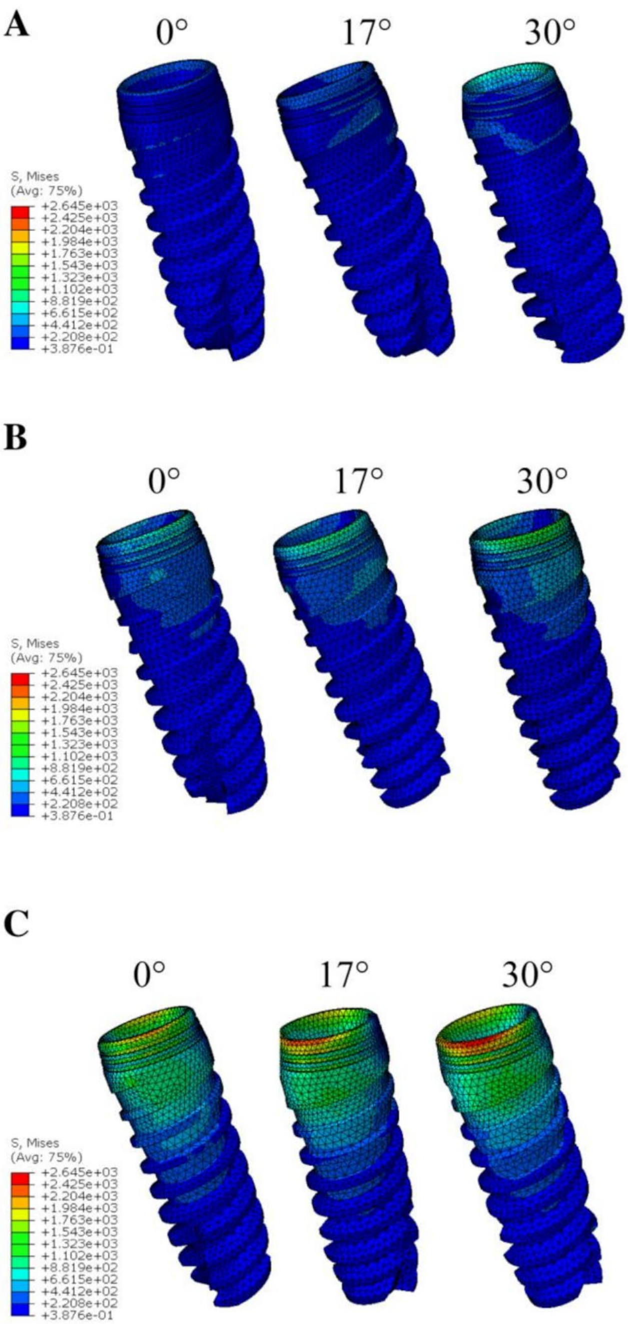

Fig. 2 The stress distribution of the implant of the MUA-implant complex models with different abutment angulation (0°, 17° and 30°). **A**, The stress distribution of implants under loading condition (**A**) **B**, The stress distribution of implants under loading condition (**B**) **C**, The stress distribution of implants under loading condition **C**

Under loading condition A, the implant with a 0° MUA exhibited a maximum stress of 437 MPa, while the implant with a 17° MUA and 30° MUA experienced maximum stresses of 843 MPa and 1185 MPa, respectively. Under loading condition B, the implant with a 30° MUA had the highest maximum stress (1422 MPa), followed by the 17° MUA (1092 MPa) and the 0° MUA (1034 MPa). Under loading condition C, the implant with a 0° MUA had the lowest maximum stress (2389 MPa). The implant with a 30° MUA experienced nearly 300 MPa higher stress than the 0° MUA implant.

Stress distribution of MUA

Figure 3 presents the stress distribution of the MUA with varies abutment angulation under different loading conditions. Under loading condition A, the straight MUA exhibited a lower maximum stress of 279 MPa compared to the 17° MUA (320 MPa) and 30° MUA (515 MPa). When the lateral force increased to 30 N (condition B), the maximum stress of the 0° MUA dramatically increased to 753 MPa. Similarly, the stress in the 17° multi-unit-abutment group and 30° multi-unit-abutment group also increase to 869 MPa and 1120 MPa, respectively. With an axial force of 100 N, the maximum stress in the 0°, 17°, and 30° MUA increased to 1646 MPa, 1906 MPa, and 2113 MPa, respectively.

Stress distribution of the prosthetic abutment

Figure 4 illustrates the stress distribution of the prosthetic abutment. Compared with the angulated MUA, the straight MUA exhibited a more evenly stress distribution. With an increasing MUA angulation, the maximum stress value also increased. In the case of a 0 N lateral force, the maximum stress of the prosthetic abutment dramatically increased from 221 N in the straight MUA group to 1726 N in the 30° MUA group. When a lateral force was applied, the stress levels were higher. When subjected to a 100 N lateral force, the maximum stress in the 30° angulated MUA (2088 MPa) is almost 8 times higher than that in the 0° MUA (309 MPa).

Stress distribution of the screws

The stress distribution of the screws (abutment screw and prosthetic screw) under different loading conditions was presented in Fig. 5.

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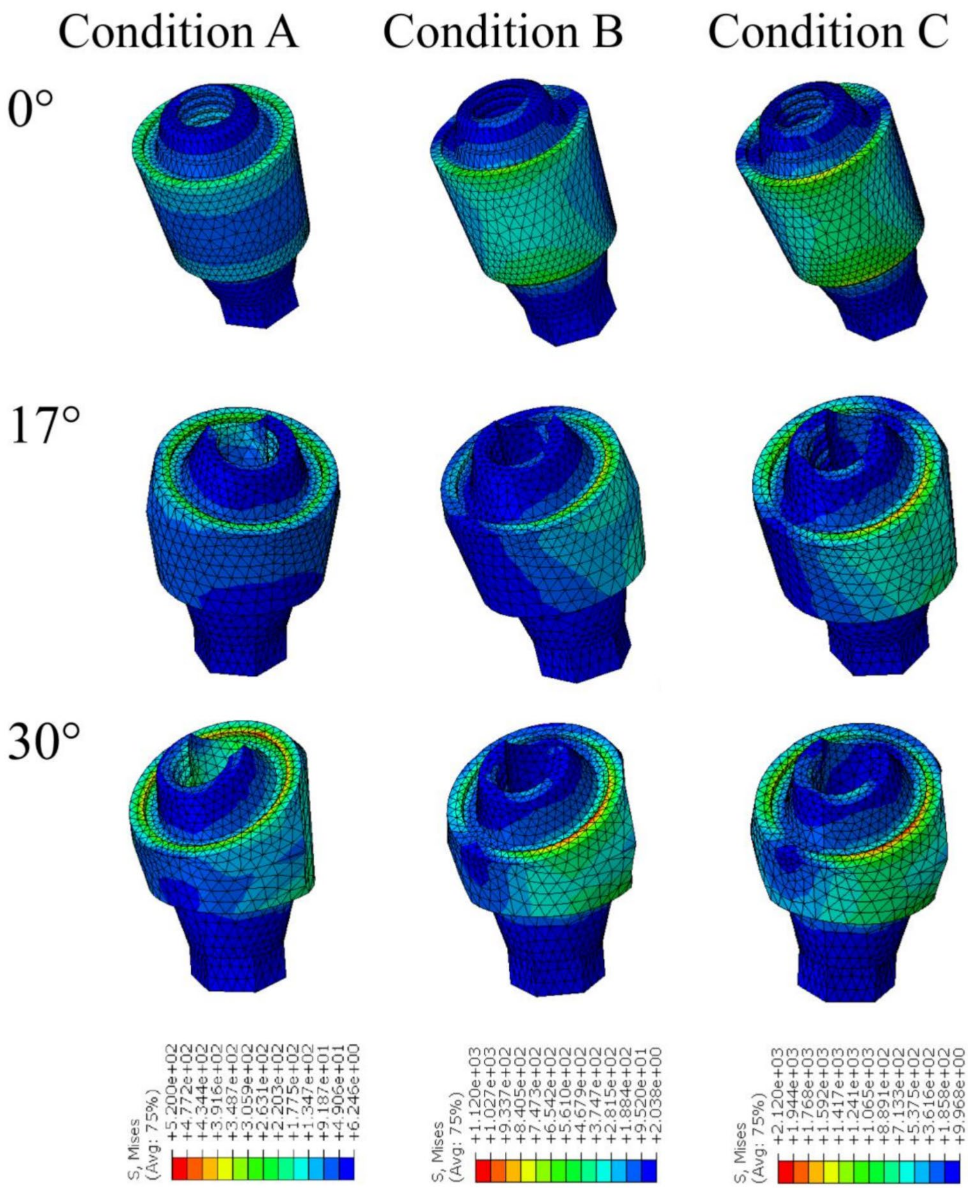

Fig. 3 The stress distribution of the MUA with varies abutment angulation under loading condition **A**, condition **B** and condition **C**

Stress distribution of the abutment screws

Under axial loading, stress concentrated in the middle region (Fig. 5A). With the addition of lateral force, it can be observed from Fig. 5B and C that the upper region (screw head) of the angulated abutment screws experienced the highest stress.

Table 2 provides the detailed results of the maximum stress on the upper, middle, and bottom parts of the abutment screw. Among the different loading conditions, the group subjected to 100 N lateral loading exhibited the highest maximum stress (985 MPa), followed by the group subjected to 30 N lateral loading (527 MPa), and the group subjected to 0 N lateral loading (130 MPa). In the angulated MUA group (17° and 30°), the maximum stress in the upper part was slightly higher (1008 MPa and 1036 MPa, respectively) compared to the straight MUA group (985 MPa).

Stress distribution of the prosthetic screws

For the prosthetic screw, the stress of angulated abutment model was concentrated near the first thread region (Fig. 5A, B and C). Table 3 summarizes the results of the maximum stress on the upper, middle, and bottom parts of the prosthetic screw. In the straight MUA group, the maximum stress of the prosthetic screw was observed in the upper part, with the maximum stress of the MUA loaded with 100 N lateral force being higher than that with 30 N lateral force (496 MPa), followed by that without lateral force (265 MPa). In contrast, for the 17° MUA group, the

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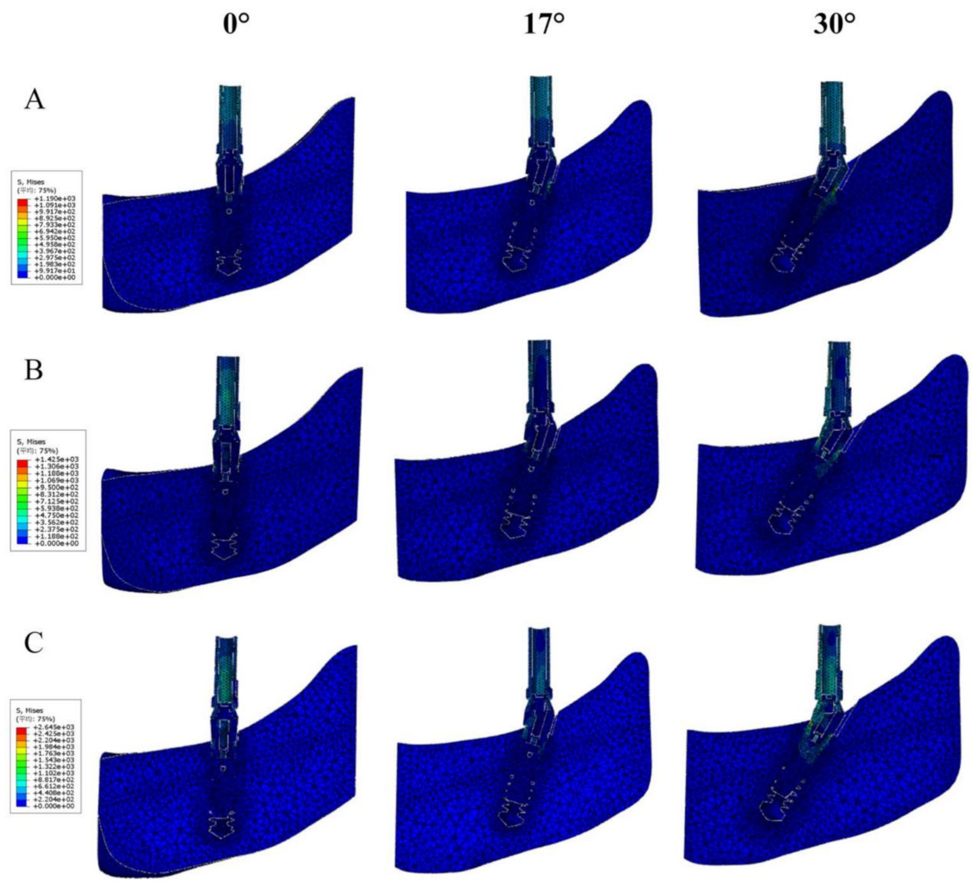

Fig. 4 The stress distribution of the prosthetic abutment of the MUA-implant complex models with different abutment angulation (0°, 17° and 30°). **A**, The stress distribution of the prosthetic abutment under loading condition (**A**) **B**, The stress distribution of the prosthetic abutment under loading condition (**B**) **C**, The stress distribution of the prosthetic abutment under loading condition **C**

major stress was concentrated in the middle part of the prosthetic screw, rather than the upper part. The maximum stress of the prosthetic screw loaded with 100 N lateral force (1428 MPa) was significantly higher than that loaded with 30 N and 0 N lateral force (779 MPa and 471 MPa, respectively). Similarly, in the 30° MUA group, the most stress was found in the middle part of the prosthetic screw. Compared to the prosthetic screw loaded with lateral force, the prosthetic screw without lateral force exhibited much lower stress, peaking at only 429 MPa.

Discussion

In this study, we used finite element analysis to construct a three-dimensional model of each component in the MUA-implant complex (0°, 17°, and 30°), including the prosthetic screw and abutment screw, which are among the most vulnerable parts in the 'All-on-four' restoration. The stress distribution of the component in the MUA-implant complex was compared under different loading conditions.

Even though numerous studies attempted to understand the mechanical behavior of the implant with MUA-implant complex by FEA, few studies simulated the MUA-implant complex with elaboration, especially the prosthetic screw and abutment screws [2, 18, 34]. Lanza et al. investigated the design of the framework in "All-on four" while the implant-abutment connection has been simplified to one screw [35]. Turker el al. constructed the maxillary and mandibular models in accordance of the "All-on four" concept without identifying the screw type [36]. A study by Hajimiragha el at.in 2014 compared the single-unit abutment with the multi-unit abutment, which almost close to the clinical situation [1]. However, because of the limitation of the numerical simulation technique, the meshes could be more dedicate. In this study, we tried to numerically construct the MUA implant complex in line with the manufacture as much as possible and the "screw in screw" manner has been developed as Fig. 4.

Angulated abutments have been used to compensate for compromised anatomical conditions in patients. Although some clinical trials have reported acceptable performance with angulated screw-retained prostheses, there are concerns about the mechanical effects of off-axis loading and preload on the screw channel, which might affect screw stability and long-term success [37]. Kao et al. found that abutment angulations up to 25 degrees increased peri-implant bone stress by 18% and micromotion levels by 30% [34]. Brosh and colleagues compared angled abutments with straight abutments and found a 3-fold increase in compressive strain at

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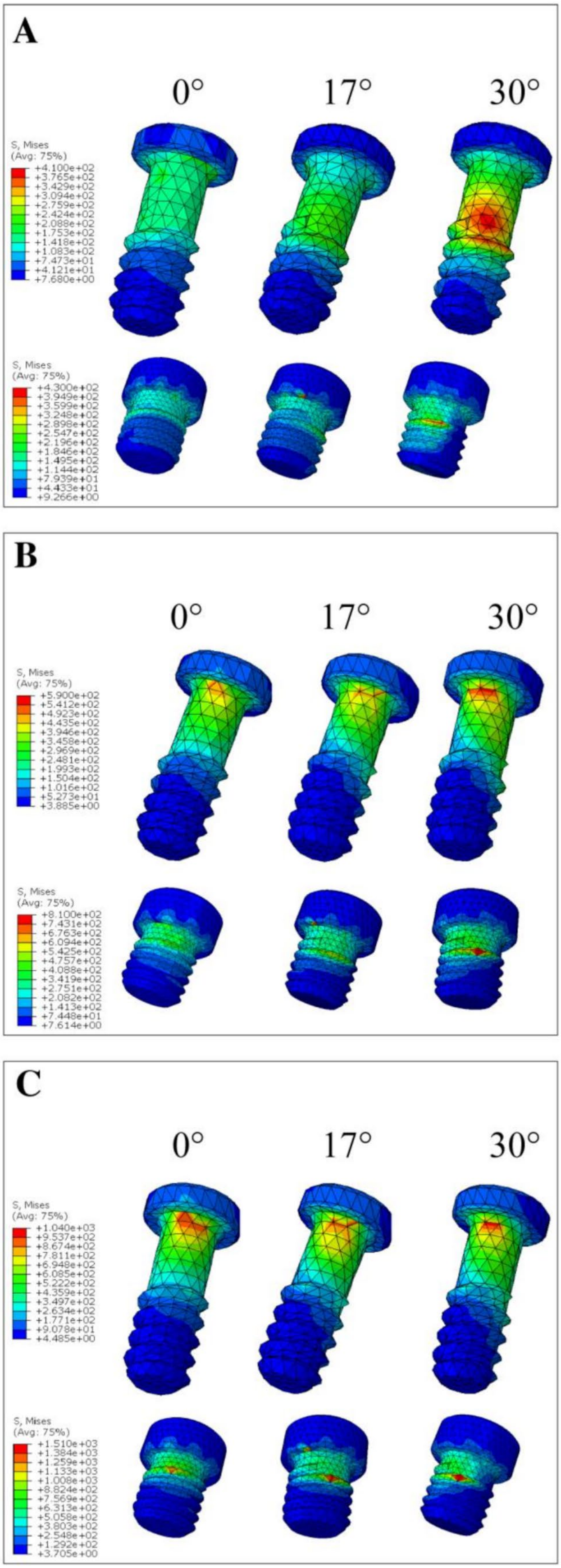

Fig. 5 The stress distribution of the screws (abutment screw and prosthetic screw). **A**, The stress distribution of screws under loading condition (**A**) **B**, The stress distribution of screws under loading condition (**B**) **C**, The stress distribution of screws under loading condition **C**

15° and a 4.4-fold increase at 25° angulated abutments [38]. In this study, we also observed that implants experienced higher stress with increasing abutment angulation. When subjected to a 200 N load along the long axis of the prosthetic abutment, implants with a 30° angulated abutment experienced nearly 2.5 times the stress (1185 MPa) compared to straight abutments (437 MPa). These results can help explain the clinical phenomenon of increased marginal bone loss in implants with angulated abutments compared to those with straight abutments [39].

When subjected to lateral force, our study revealed a significant increase in the maximum stress of the implant, particularly in the implant neck,. Compared to the implant without lateral force, the maximum stress was eight times higher under a 100 N lateral force (2389 MPa). Similar findings were reported by De Faria Almeida et al. [40], who observed amplified stress in bone tissue, implants, and prosthetic components under oblique loading conditions. Given that lateral force is an inevitable consequence of masticatory loading [21, 25, 41], it is crucial to maintain controlled and balanced biting force to minimize the risks of biological and mechanical complications in patients undergoing 'All-on four' treatment with angulated MUA anchoring systems [42, 43].

Long-term studies have consistently reported mechanical complications of screw-retained prostheses, such as screw loosening and fracture [3, 44, 45]. After analyzing screw failures in clinical practice, Katsavochristou et al. reported that the majority of screw fractures occurred at the screw body rather than the screw head [45]. This study found a different stress distribution pattern between the prosthetic screw and abutment screw. For the prosthetic screw, the stress of angulated abutment model was concentrated near the first thread region. For the abutment screw, there is greater possibility of fracture in the screw heads. However, it is important to note that the stress distribution of the both abutment and prosthetic screw were greatly influenced by the lateral force (Tables 2 and 3). Therefore, reducing lateral force is essential to lower the risks of screw loosening and fracture.

In this study, from the results of the maximum stress of the abutment screw and prosthetic screw in Tables 2 and 3, it could be apparently observed that the prosthetic screws suffered higher stress concentration than the abutment screw. The maximum stress of the prosthetic screw loaded with 100 N lateral force (1509 MPa) in 30° MUA group was greatly higher than that of the abutment screw (1036 MPa). In addition, the prosthetic screw being relatively smaller

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Table 2 The maximum stress (MPa) on the upper, middle and bottom part of the abutment screw

Loading conditions	0° MUA abutment screw group (MPa)			17° MUA abutment screw group (MPa)			30° MUA abutment screw group (MPa)		
	Lower part	Middle part	Upper part	Lower part	Middle part	Upper part	Lower part	Middle part	Upper part
Condition A	5	252	130	31	276	235	21	406	133
Condition B	6	189	527	45	275	548	45	294	586
Condition C	8	323	985	81	330	1008	82	320	1036

Table 3 The maximum stress (MPa) on the upper, middle and bottom part of the prosthetic screw

Loading conditions	0° prosthetic screw group (MPa)			17° prosthetic screw group (MPa)			30° prosthetic screw group (MPa)		
	Lower part	Middle part	Upper part	Lower part	Middle part	Upper part	Lower part	Middle part	Upper part
Condition A	8	90	265	38	417	268	41	429	191
Condition B	11	255	496	65	779	456	81	806	295
Condition C	13	431	707	83	1428	737	132	1509	518

than the abutment screw, making it a potential weak point in cases of prosthetic complications [5]. Hence, clinicians should monitor prosthetic screw integrity during follow-up visits to prevent complications.

This study has several limitations that should be acknowledged. Firstly, the exclusion of the crown in the simulation was intentional to eliminate confounding factors associated with crown design. Parameters such as cusp inclination, occlusal contact distribution, crown contour, and material properties are known to significantly influence stress distribution around dental implants [29]. For example, Falcon-Antenucci et al. [30] demonstrated that a 10° increase in cusp inclination elevates shear forces and crestal bone stress, while da Rocha Ferreira et al. [46] reported that reduced prosthetic height decreases marginal bone stresses. Given the critical role of the crown in clinical practice, future studies should investigate the influence of crown design and material properties on the biomechanical behavior of the MUA-implant complex to provide a more comprehensive understanding of stress distribution in implant-supported restorations. Secondly, the loading conditions applied in this study were simplified to focus on the effects of axial and lateral forces on the MUA-implant complex. However, in clinical practice, loading patterns are far more complex, involving dynamic and multidirectional forces. Future studies should incorporate more realistic loading scenarios to enhance the clinical relevance of the findings.

Conclusion

Within the limitations of this study, the following conclusions can be drawn:

1. Increasing the abutment angulation leads to higher stress on the implant, which may be associated with potential bone loss, particularly in the implant neck.
2. Lateral forces significantly increase the maximum stress on the implant, particularly in the neck region of the implants with angulated MUA.
3. There is a distinct stress distribution pattern between the prosthetic screw and abutment screw, with the former experiencing higher stress concentration than the latter, indicating the importance of regular monitoring about the prosthetic screw integrity.

Acknowledgements Nothing to declare.

Author contributions Xiao-Ning Guo and Zi-Heng Wen were responsible for finite element simulation and project design. Yuqing Zhang and Dong Lin were involved in the literature reviewing, writing of the paper and data interpretation. All the authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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