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Biomechanical analysis of All-on-4 implant supported framework using different materials across various clinical practice

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Abstract

Background With the global aging trend, the number of edentulous individuals is steadily increasing. All-on-4 implant restoration can greatly recovery masticatory function in edentulous patients. This study aims to determine the effect of framework material and cantilever length on the stress distribution in All-on-4 implant components using three-dimensional finite element analysis, thereby providing clinicians with insights into the design of All-on-4 superstructures to improve patient outcomes.

Methods Five framework models with cantilever lengths of 0 mm, 3 mm, 6 mm, 9 mm, and 12 mm were established, with the cantilever material selected as either titanium (Ti) or polyetheretherketone (PEEK). The jawbone, implant, and framework models were then assembled, with four implants placed in the jawbone according to the classic All-on-4 design and connected to the framework via abutments. Finally, occlusal forces were applied to the framework. Finite element analysis was used to obtain the stress and strain distribution in the jawbones, as well as the stress distribution within the implants and the frameworks.

Results Overall, the use of a PEEK framework demonstrated better stress distribution in the jawbone due to its elastic modulus, the maximum stress of which is 26% lower at most than Ti. Although PEEK frameworks showed lower stress overall, implant stress increased, particularly for cantilever lengths over 6 mm, reaching values up to 2.6 times higher than in titanium.

Conclusions Cantilever length and framework material are interrelated factors that both influence the stress distribution in the All-on-4 system. A PEEK framework can serve as an alternative to titanium framework in short cantilever lengths (under 6 mm), offering slightly better mandibular protection. Titanium is preferable for lengths between 6 mm and 9 mm to reduce mechanical risk. Cantilever lengths exceeding 12 mm are discouraged due to increased stress.

Trial registration Not Applicable.

Keywords All-on-4, Finite element analysis, Cantilever length, Polyetheretherketone, Titanium

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Background

In the context of global aging, the prevalence of edentulism among individuals aged 65 and older can range from 6 to 69% [1]. This condition severely impacts patients' ability to chew, eat, speak, and maintain their appearance. The All-on-4 concept represents a widely applied and highly successful strategy for edentulous rehabilitation using dental implants [2]. This approach entails the placement of four implants in either the maxillary or mandibular bone, supporting a full-arch fixed prosthesis. Based on the principle of immediate loading, and has since been validated through extensive clinical practice [2, 3]. When chewing forces are applied, the stress is transmitted from the framework to the implants and the jawbone. The amplification of stress by cantilever leverage may influence marginal bone loss and restoration prognosis [4]. The magnitude and distribution of stress in All-on-4 system significantly influenced by the length of cantilever and the material of framework [5].

Cantilever length (CL) is defined as the distance from screw-access openings on framework of the posterior implant to the most distal occlusal point [6]. The determination of cantilever length is a subject of controversy. While a longer cantilever length can enhance masticatory efficiency, an excessively extended cantilever may cause more stress to bone thus heighten the risk of biological and mechanical complications [7]. The incidence of mechanical complications in fixed prostheses with cantilevers can reach up to 20.3% [8]. Kim et al. found that long CL in implant-supported fixed dental prostheses correlate positively with increased mechanical complications and bone loss ≥ 1.5 mm [4, 9]. Originally, the founder Dr. Malo proposed cantilever extension of 2–3 teeth in scenarios with relatively dense mandibular bone. However, subsequent extensive clinical experience has led to the adoption of a more conservative approach, typically restoring only one molar unit [2]. Scholars have proposed utilizing the ratio of cantilever lengths to anterior-posterior spreads (CL/AP) to determine more specific values of CL. Overall, the recommended CL/AP ratios vary from 0.3 to 2; however, the reliability of using CL/AP to calculate cantilever length has not been validated by prospective studies [10]. However, there are some limitations in the research regarding cantilever length. Clinical research faces the challenge of accurately measuring the cantilever segment. The commonly used Boley gauge has limited measurement accuracy, reaching only 0.5–1 mm [11]. The aforementioned studies on CL/AP predominantly utilize titanium frameworks, while research on the application of other novel framework materials remains limited.

Besides CL, the material composition of the framework also affects the prognosis of All-on-4 restorations [5, 11]. Titanium and its alloys are commonly used in All-on-4 frameworks. However, they can result in significant stress shielding due to their mechanical properties, which differ greatly from those of cortical bone [12]. Recently, polyetheretherketone (PEEK), valued for its optimal rigidity and elastic modulus akin to that of cortical bone and dentin, has gained increasing application in implant restorations [13]. Miguel et al. reported that the use of PEEK frameworks and hybrid PEEK-acrylic resin prostheses in All-on-4 restorations reduces marginal bone loss and enhances long-term implant biological outcomes, attributed to the shock-absorbing properties of PEEK [14]. Zoidis et al. reported modified PEEK frameworks leveraging superior elastic properties to mitigate occlusal force impacts, thus safeguarding both the prosthesis and opposing dentition [15]. Due to the superior fracture behavior of PEEK, it is less likely to experience screw loosening and framework fractures during long-term masticatory activities [16]. This material presents an alternative to conventional metal framework for All-on-4 restorations. Overall, PEEK materials demonstrate superior elasticity and fracture behavior compared to metallic materials while maintaining fracture resistance. They can be manufactured into lighter frameworks and are suitable for implant restorations in patients with metal allergies [17]. However, on the other hand, the mechanical strength and hardness of PEEK material are inferior to the traditional titanium framework, and it is considered to have weaker compressive strength.

Three-dimensional finite element analysis (FEA) enables precise simulation of the implant system and maxillofacial interactions within a reconstructed patient-specific model using simulation software. This method readily allows for adjustments to the framework's material, cantilever length, and occlusal load. Mechanical analysis software visually displays the internal and external stress-strain distributions, offering detailed quantitative outputs. This approach aids in identifying potential risks prior to undertaking costly and time-consuming clinical trials. However, the precision, fidelity, and computational power of the model reconstruction significantly influence the accuracy of FEA results [18].

This study employs FEA to explore the impacts of stress and strain on the jawbone, implants, and frameworks, using PEEK and Ti frameworks with five varying cantilever lengths in All-on-4 restoration. Driven by the objectives of precision medicine, this preclinical predictive approach aids in tailoring clinical decisions about framework material and cantilever length restoration, thereby improving the prognosis of All-on-4 restorations and minimizing complications. The null hypothesis states that the material of the framework and cantilever length do not influence the microstrain-stress distribution around the implant and the All-on-4 system.

Methods

Our research was approved by West China hospital of Stomatology review board. This study constructed five All-on-4 three-dimensional finite element models, with cantilever length as a variable. The cantilever lengths were 0 mm, 3 mm, 6 mm, 9 mm, and 12 mm to simulate clinical conditions [4, 19].

Each model included 4 implants (Nobel Biocare, 4.3 mm in diameter, 13 mm in length), abutments (two straight abutments and two 30° angled abutments), An oral scanner (TRIOS 3, 3Shape A/S, scanning accuracy of 10 mm) was used to scan the implant [20]. The data were imported in standard tessellation language (STL) format into reverse engineering software (Geomagic Studio; 3D Systems Inc). The mandible model was derived from CT data of an edentulous patient. CT images were imported in digital imaging and communications in medicine (DICOM) format into Mimics (21.0, Materialise) software and converted to STL format. Reverse modeling was done in Geomagic Studio, resulting in a mandible model with a cortical bone thickness of 2 mm. Frameworks with different cantilever lengths were created using CAD software (SolidWorks 2020; Dassault Systems SolidWorks Corp). Gingival tissue with a thickness of 2 mm was modeled using Geomagic Studio and SolidWorks [21].

The models of each element were assembled in SolidWorks. All implants were placed in identical positions: the two mesial implants were symmetrically and vertically inserted into the lingual fossa of the lateral incisors on both sides. The two distal implants were symmetrically and 30°distally tilted, with the emergence point at the distal aspect of the second premolar.

The models were imported into the FEA software (ANSYS 18.2.2; ANSYS Inc) in parasolid format. All components were defined as homogeneous, isotropic, and linearly elastic materials. Material properties, such as Poisson's ratio and elastic modulus, were assigned based on previous studies [22]. The specific values are summarized in Table 1. The model included 14,569,970 nodes and 10,452,160 elements (Fig. 1), and a convergence test was performed to ensure accuracy and computational efficiency. Full integration at the interfaces was ensured by anchoring the relative nodes between elements [23].

Table 1 The Young's modulus and Poisson's ratio of each material involved in the model

Materials	Young's modulus (MPa)	Poisson's ratios
Implant	110,000	0.35
Abutment	110,000	0.35
Framework (PEEK)	4100	0.40
Framework (Ti)	110,000	0.35
Cortical bone	13,700	0.30
Cancellous bone	1370	0.30
Gingiva	3	0.47

Abbreviations: PEEK, polyetheretherketone; Ti, titanium

Boundary constraints were set at the condyles and the chin of the mandible. In the model with a CL of 0, vertical loads of 450 N and 100 N was applied along the long axis of the distal and mesial implants on both sides [24]. For every additional 3 mm of cantilever length, the vertical occlusal force was increased by 50 N. The stress loading points and magnitudes for different models are summarized in Fig. 2. The solid arrows indicate two forces, 450 N and 100 N, whose magnitudes and application points remain constant. The 450 N masticatory force was evenly distributed from the mesial implant to the mesial portion of the distal implant, while the 100 N masticatory force was applied to the distal implant. The dashed arrows represent forces applied to different colored blocks: 50 N to the blue block, 100 N to the yellow block, 150 N to the orange block, and 200 N to the red block. These forces correspond to the biting force at the end of the cantilever for CL lengths of 3 mm, 6 mm, 9 mm and 12 mm, respectively. The maximum occlusal force is positively correlated with masticatory efficiency. The force application pattern was determined based on the range of occlusal force and previous studies [24].

After loading the stress, the von Mises stress distribution in the implants, abutments, frameworks, and cortical bone, as well as the strain in the cancellous bone, were calculated.

Results

Through FEA and data statistics, we visually observed the stress distribution in frameworks, implants, and jawbones, and obtained the trend of stress value changes under different cantilever lengths and framework materials.

Stress of frameworks

In all models, stress on the framework predominantly concentrates around the screw-access openings of the distal implants' abutments (Fig. 3). Figure 4 demonstrates the trend in average stress of frameworks across different cantilever lengths for two types of implants. At the same cantilever lengths, framework stress in Ti group is 29.4–54.7% higher than that in PEEK group. As the length of cantilever increases, the rate of stress increase also gradually becomes larger. For example, increasing the cantilever length of the PEEK framework from 0 mm to 6 mm results in a 52.7% increase in framework stress, and extending it from 6 mm to 12 mm leads to a 172.43% increase (rise 63.59% from 6 to 9 mm, 66.5% from – 12 mm).

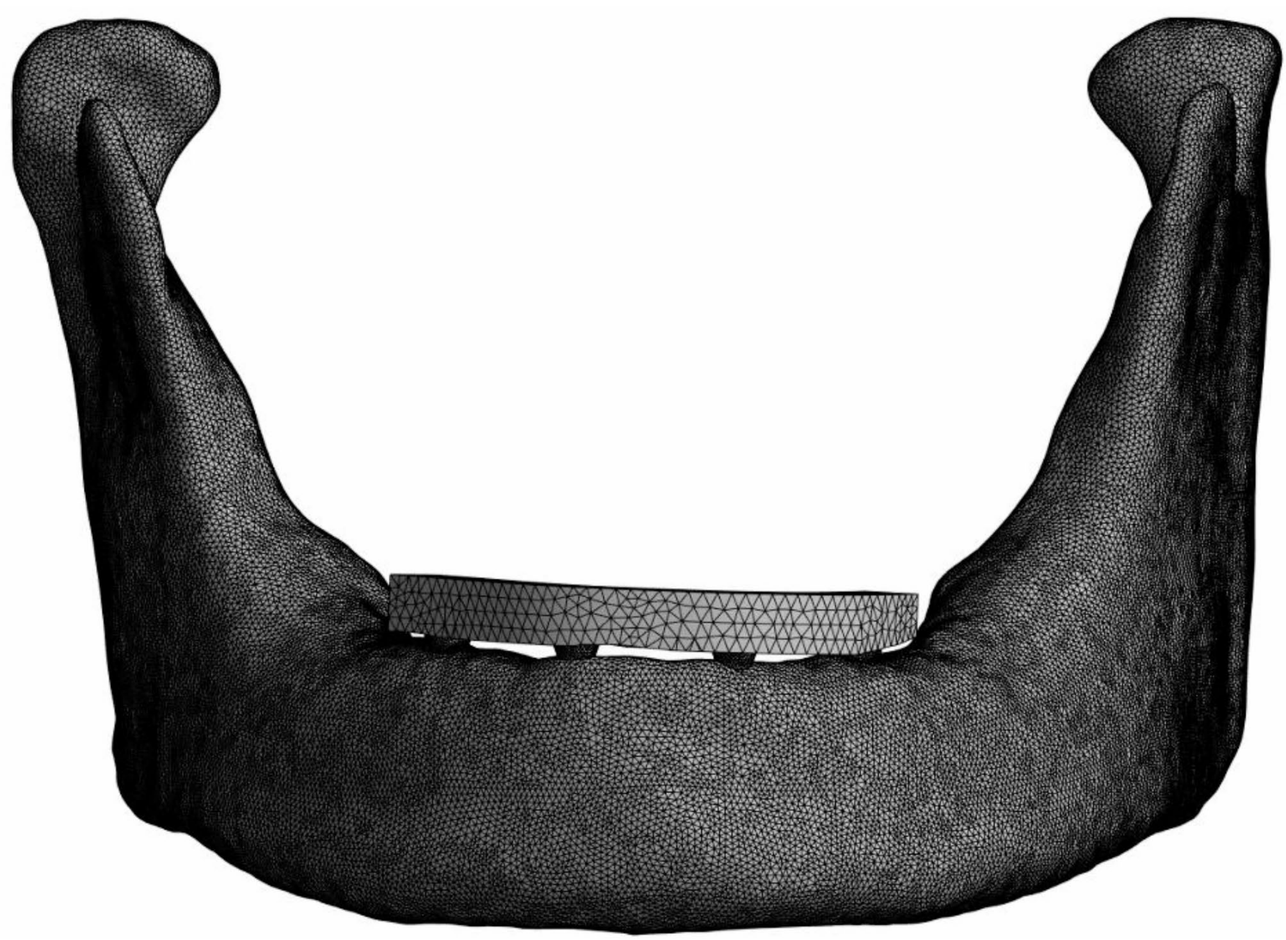

Fig. 1 All-on-4 mesh model. A mesh generated on jawbone, framework and implants

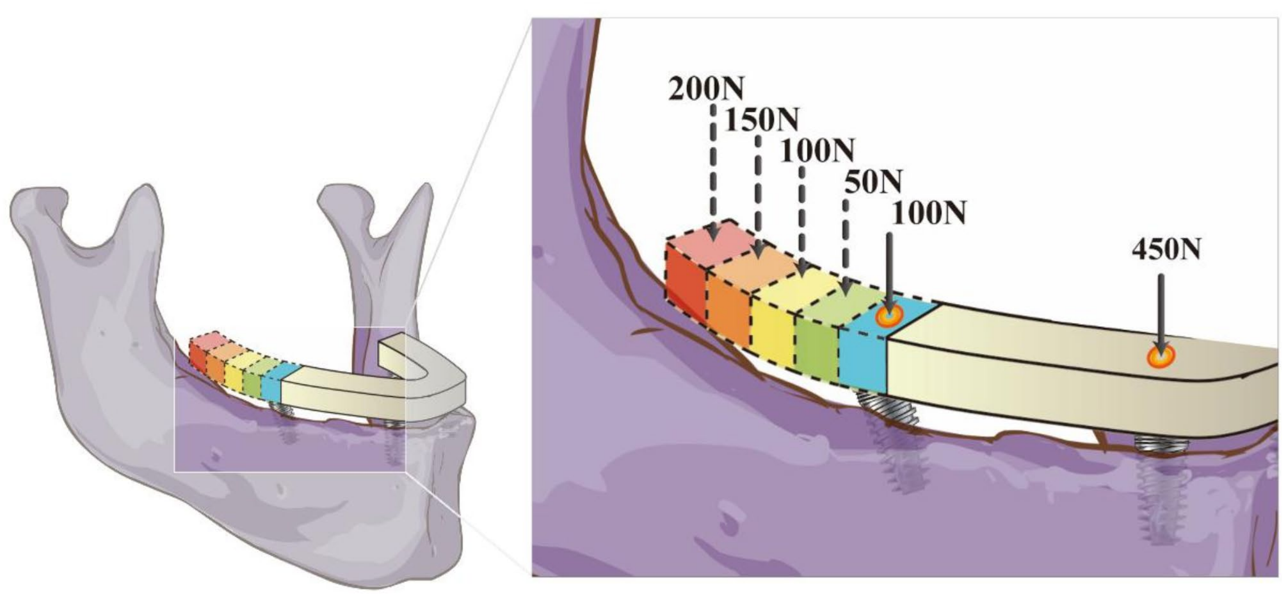

Fig. 2 Occlusal force application patterns for frameworks with different cantilever lengths (Take the right side as an example)

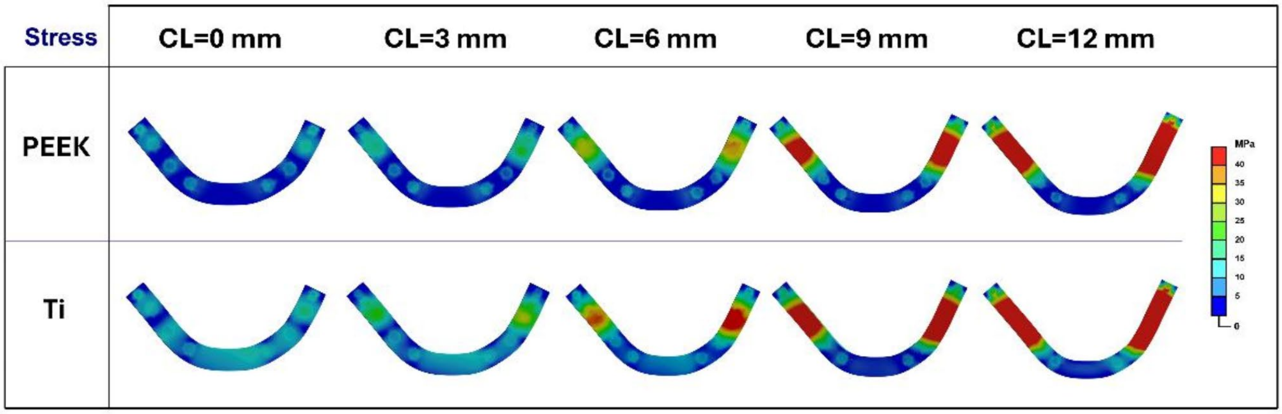

Fig. 3 Von Mises stress distribution of frameworks within each model

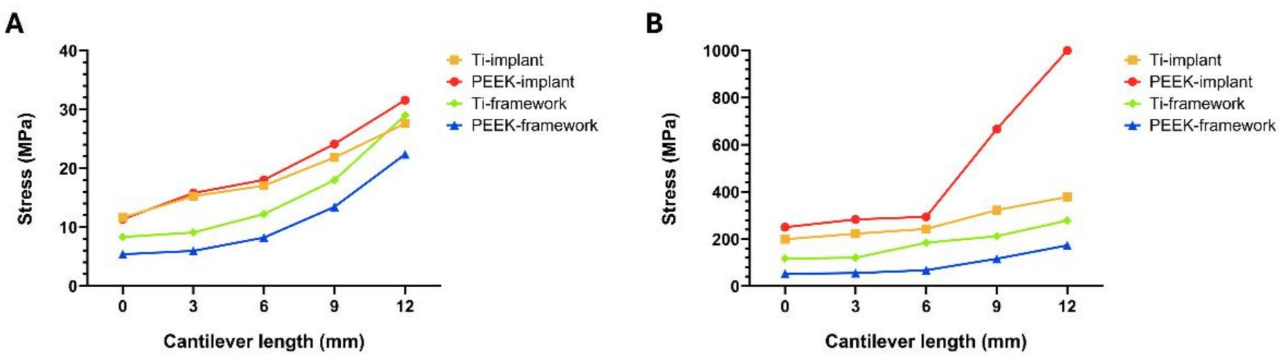

Fig. 4 Relationship between cantilever length and the average and maximum stress values in frameworks and implants. (**A**) Average stress of implants and frameworks. (**B**) Maximum stress of implants and frameworks

Stress of implants

Stress is mainly distributed around the screw-access openings and at the interface between the implant and the abutment of the distal implants, as illustrated in Fig. 5, with peak values occurring at the buccal cervical area of the angled implant. According to Fig. 4, when the cantilever length is ≤6 mm, the average stress values in the implants of the Ti and PEEK framework groups are comparable, with differences < 6%, and the peak stress value is marginally higher in PEEK. However, as the cantilever length exceeds 6 mm, the peak stress values in the PEEK group escalate significantly, attaining 2.6 times than those of Ti group at a cantilever length of 12 mm.

Stress and strain within jawbones

Figure 6 illustrates the stress distribution within the jawbone. The stress in the jawbone is primarily localized around the distal area of the posterior implants. Figure 7 details the variations in mean bone stress around the implants and cancellous bone strain values after applying bite force to Ti and PEEK frameworks with varying cantilever lengths. As the cantilever length increases, there is a progressive increase in stress values in the jawbone. The average jawbone stress increases by approximately 67.5% (Ti) and 62.3% (PEEK) as cantilever length extends from 0 to 12 mm. When 0 < CL < 6 mm, the Ti and PEEK framework groups display similar values of jawbone stress. When the CL ranges from 6 to 12 mm, the average stress in Ti group slightly exceeds that of PEEK group, with a difference of 1.84×10^{-2} MPa at a cantilever length of 12 mm. The maximum stress shows a more significant difference. At a cantilever length of 12 mm, the maximum bone stress in Ti framework is 26% higher than that in PEEK framework. The difference enlarges with increasing cantilever length.

Figure 8 shows the equivalent elastic strain distribution in the cancellous bone. Strain of jawbone is chiefly concentrated at the distal areas of these implants too. The overall trend of strain values is similar to that of stress values.

Discussion

The choice of framework material and cantilever length affects the microstrain-stress distribution, leading to the rejection of the null hypothesis. The design of All-on-4 supra restoration requires further validation and practice to improve their therapeutic efficacy and long-term prognosis, and more new materials should be taken

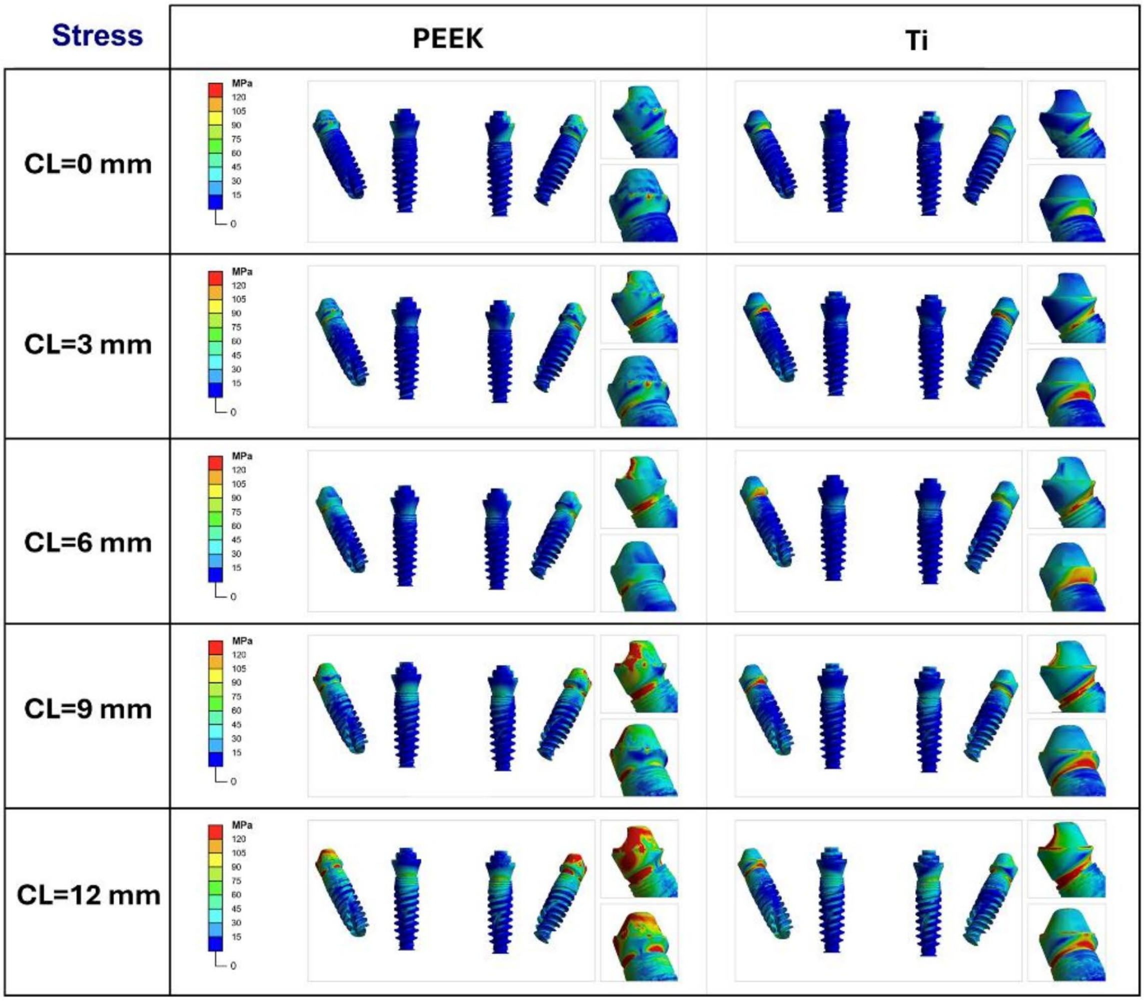

Fig. 5 Von Mises stress distribution patterns of implants within each model. The central image depicts the stress distribution among four implants. The inset in the upper right corner enlarges the view of the stress distribution in the buccal cervical area and abutment interface of the angled abutment of the right distal implant. The lower right inset offers a detailed depiction of the stress distribution within the mesial cervical region of the aforementioned abutment

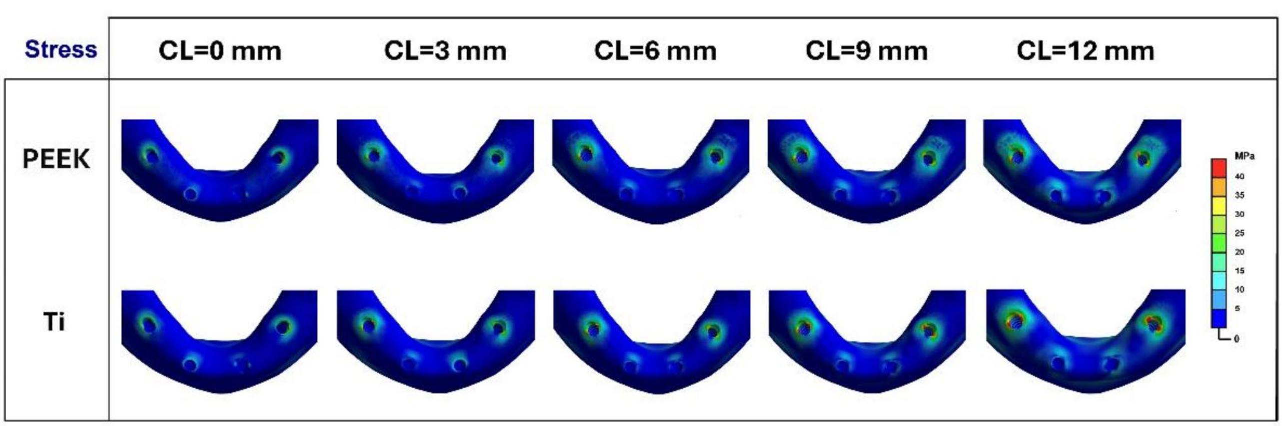

Fig. 6 Von Mises stress distribution of jawbone. The color scale represents a range of measured values

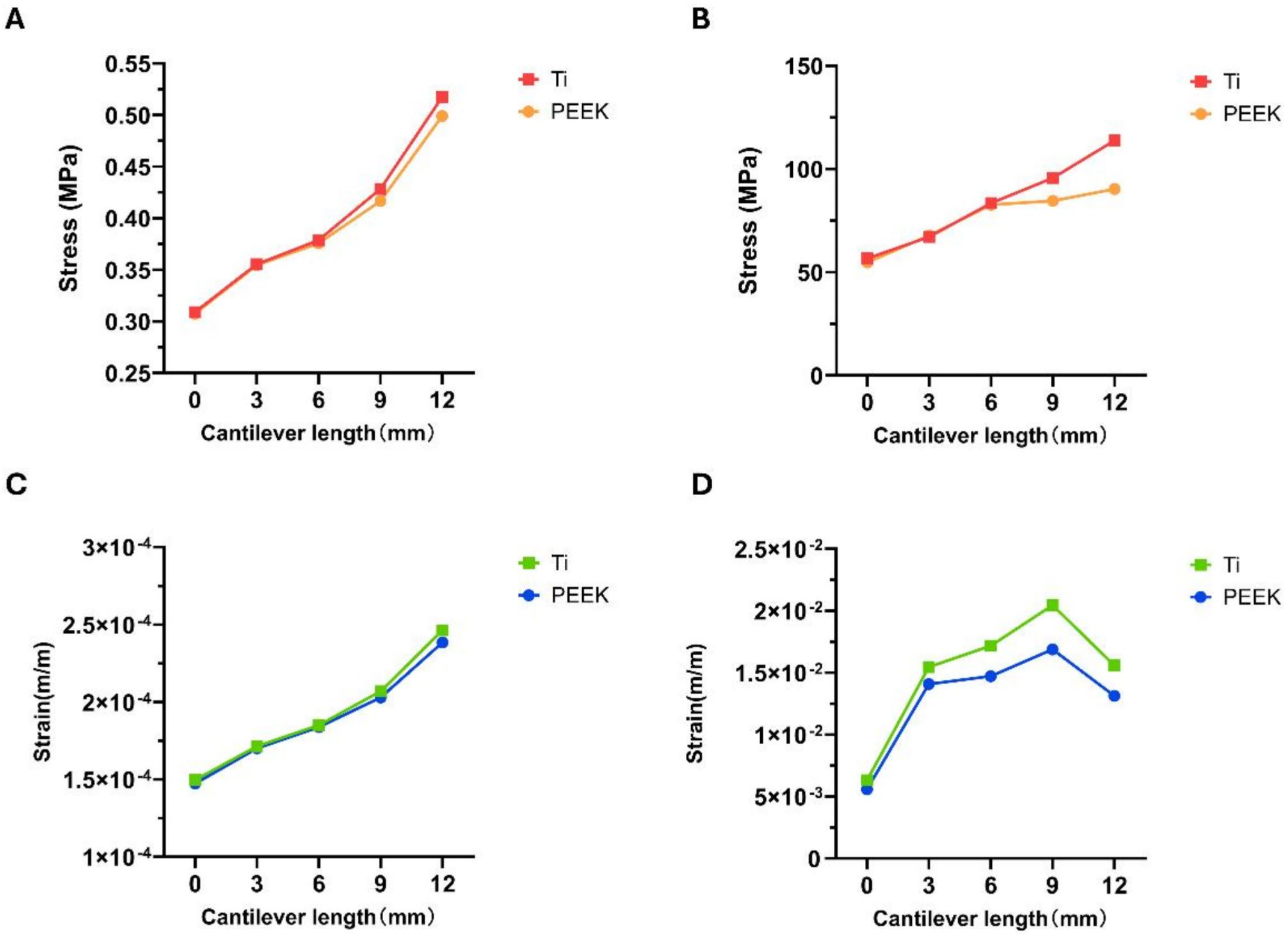

Fig. 7 The average and maximum stress and strain values of bone. (**A**) Average stress of bone. (**B**) Maximum stress of bone. (**C**) Average strain of cancellous bone. (**D**) Maximum strain of cancellous bone

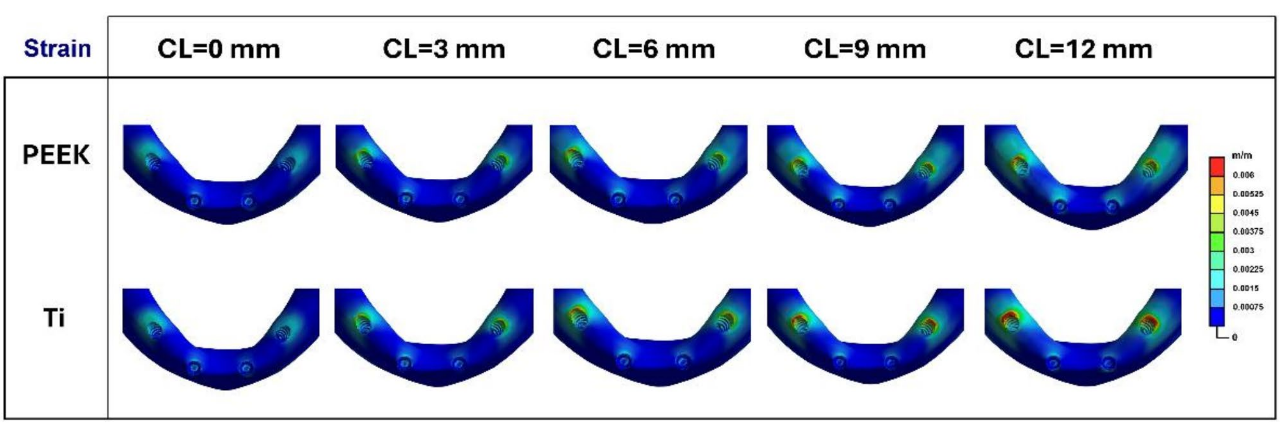

Fig. 8 Distribution of strain distribution in cancellous bone of all models. The color scale represents a range of measured values

into consideration. Nearly all implant-supported dentures involve the use of cantilevers, and the All-on-4 is no exception [7]. A short cantilever is not conducive to restoring masticatory function and may increase the risk of prosthesis fracture due to concentrated attrition on the prosthesis [11]. Conversely, longer cantilever can increase chewing efficiency but may result in greater marginal bone loss and technical complications [4]. As previously mentioned, excessive stress on the jawbone is associated with bone loss, while stress concentration on the framework and implants is linked to fractures.

Therefore, we conducted a study on the material selection and the design of the cantilever length for the framework.

Our study demonstrates that in the classical All-on-4 mandibular technique, the stress on frameworks, implants, and stress/strain on bones escalate with increasing cantilever length.

Materials of framework have significant impact on All-on-4 system. In our study, PEEK was demonstrated a lower tendency to generate stress concentrations under applied force (54.7% lower at most), effectively transmitting it to implant (Fig. 4). This finding aligns with Aboelfadl et al.'s study, where they compared zirconia with polyetherketoneketone (PEKK), and found that PEKK, with its lower elastic modulus, transferred more stress to the implant [25]. The stress on implants predominantly occurs in the distal cervical area, consistent with previous research [21]. These regions, where the abutments interface with both the implants and the framework, are prone to structural fatigue with long-term use. Materials with a higher elastic modulus have smaller relative displacements between internal atoms or molecules, resulting in faster stress propagation. PEEK's Young's Modulus (4.1 GPa) is much lower than Ti (110 GPa). Research indicates that under impact loading, PEEK is more efficient at energy absorption than titanium alloys and also shows greater ductility [26]. Therefore, PEEK, with its lower elastic modulus, possesses better stress buffering effects. Additionally, high elastic modulus can lead to stress shielding phenomena. Studies have shown that stress shielding from PEEK hip prostheses is reduced by 48% compared to Ti alloy prostheses, with a 30% decrease in femoral head absorption [27]. So when PEEK is used as a support structure, it can more effectively transmit stress, resulting in a more reasonable stress distribution within the implant system [28]. The absence of the periodontal ligament's cushioning effect makes implants more prone to overload-induced marginal bone loss (MBL) [29]. Therefore, PEEK frameworks are better suited for creating an implant system that ensures uniform stress distribution and provides cushioning behavior, which helps protect the jawbone. Our results indicate that the PEEK group demonstrated only a modest advantage in reducing jawbone stress. Therefore, within the strain range of the jawbone that stimulates bone formation, either material can be chosen. However, selecting PEEK material to reduce jawbone strain may slightly enhance osseointegration, particularly in the immediate loading All-on-4 restoration method [30].

Another influence factor is cantilever length. Regarding the stress on frameworks, our results demonstrate that an increase in CL results in a corresponding increase in stress. Beyond a CL of 9 mm, the stress on the framework substantially intensifies, suggesting caution in opting for longer cantilever lengths. The stress values in Ti groups remain significantly below its respective yield stresses (Ti = 340–946 MPa) [31]. However when CL ≥ 9 mm, the stress of framework exceeds PEEK's yield stress (110 MPa) [32]. This indicates that under normal masticatory forces, Ti is unlikely to undergo irreversible deformation or fracture. We suggest using Ti frameworks when CL ≥ 9 mm to avoid mechanical complications.

Some interesting phenomena occurs in the stress-strain distribution and numerical trend. Despite variations in stress loading patterns, FEA shows that the jawbone stress in implant-supported full-arch dentures is primarily concentrated in the jawbone region corresponding to the neck of the most distal implant [33]. Similar results have been observed in in vitro photoelastic studies, consistent with our findings. The stress of jawbone in PEEK group was smaller than that in Ti group, which is consistent with the conclusion of Haroun et al. They concluded that using materials with lower elastic modulus like PEEK can reduce stress transfer to the jawbone [34, 35]. When the 6 ≤ CL < 9 mm, a marked increase in average bone stress is observed in the PEEK group. This phenomenon may be attributed to followed causes: firstly, the simultaneous increase in both the CL and the bite force results in nonlinear increase. Secondly, stresses exerted at the ends of long cantilevers generate greater deformation thus cause additional shear or tensile forces at these critical junctions. Thirdly, due to the lower elastic modulus of PEEK, it deforms more easily, resulting in greater strain and consequently more lateral forces [32]. When the 9 ≤ CL < 12 mm, the growth slope for average stress has further increase. When the CL is 12 mm, the average cortical bone stress for both materials is 1.67 times (Ti) and 1.62 times (PEEK) that of the non-cantilever group. For the maximum values, when 6 mm ≤ CL < 12 mm, the increase in jawbone stress in the PEEK group is gradual, which corresponds to the rapid increase in implant stress in PEEK group for the same CL range. It is hypothesized that due to the increased deformation of PEEK, even leading to plastic deformation, stress redistribution occurs, and the implant bears most of the stress along the propagation path. When the CL is 12 mm, The maximum jawbone stress in the Ti group surpasses the cortical bone yield strength of 104 MPa reported by Bayraktar, which is considered to potentially lead to bone fatigue and thereby increase the risk of fracture [33, 36]. Notably, when the CL is 12 mm, the maximum strain values of cancellous bone for both Ti and PEEK decrease. This could be attributed to the fact that as the cantilever length increases, the lateral force on the implant also rises, leading to significant stress concentration in the distal cortical bone (Fig. 6). The cancellous bone's stress is more derived from the transmission of stress from the cortical bone rather than from the implant. Due to the large contact area between the cortical bone and the cancellous bone, the strain distributes more evenly, resulting in a decrease in peak strain and an increase in average strain. Similar phenomena were observed in the photoelastic study by Wang et al., where they found that as the cantilever length increased, the stress increase in bone at the implant crest was more significant than at the apical region [10].

There are also some limitations. In our study, we assumed complete bonding at all interfaces, neglecting the impact of interfacial friction and shear stress. We also employed a simplified model of the framework instead of a detailed prosthesis for stress analysis. These simplifications could potentially compromise the accuracy of our findings.

Our study analyzed the stress values and stress-strain distributions for PEEK and Ti frameworks with different cantilever lengths, assisting clinicians in devising more accurate and tailored implant restoration plans. To sum up, the selection of framework materials has varying impacts on stress/strain values for different cantilever lengths. We recommend carefully setting cantilever lengths of 12 mm and above, as stress/strain values exhibit an exponential increase. When CL ≤ 6 mm, PEEK demonstrated a slight advantage in reducing mandibular stress due to its cushioning capability, making it a potential alternative to Ti in short cantilever framework. When 6 mm < CL ≤ 9 mm, we recommend using Ti as the framework material to reduce the probability of implant-related mechanical complications occurring. Future studies should aim to refine the use of FEA as a preoperative planning tool for All-on-4 procedures, enhancing automation and efficiency through the integration of more extensive patient data and designs. Furthermore, corroborating these methodologies with clinical data is essential to enable precise and intelligent design of complex implant surgeries.

Conclusions

Our findings reject the null hypothesis and demonstrate that in the All-on-4 implant system, framework design—including cantilever length and material selection—affects the microstrain-stress distribution in the framework, implants, and jawbone under masticatory forces. PEEK exhibited lower jawbone stress at all cantilever lengths, but for longer cantilevers (6 mm < CL ≤ 12 mm), the stress concentration in the PEEK group's framework and implants was more pronounced. When CL is 12 mm, the stress on PEEK framework itself and the jawbone stress in Ti group both exceeded their respective yield stresses. Clinicians should incorporate the design of the superstructure into their considerations when performing All-on-4 implant restorations to ensure optimal stress distribution and improved prognosis.

Abbreviations

AP	Anterior-posterior spreads
CL	Cantilever length
FEA	Finite element analysis
MBL	Marginal bone loss
PEEK	Polyetheretherketone
PEKK	Polyetherketoneketone
Ti	Titanium

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Author contributions

X. Chen conducted the experimental design and drafted the manuscript. Z. Xu contributed to visualization and figure preparation. K. and Xibo Pei assisted with editing and reviewing the manuscript. R. Li provided consistent technical support throughout the study. Q. Wan proposed the experimental concept and ideas, offered guidance on clinical issues, and provided funding support.

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Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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