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Comparison of biomechanical performance of titanium and polyaryletheretherketone miniscrews at different insertion angles: A finite element analysis

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Abstract

INTRODUCTION: Only miniscrews [temporary anchoring devices, (TADs)] can provide absolute anchorage during orthodontic treatment. Titanium (Ti) is a fundamental material used in the production of miniscrews, but it has many disadvantages. Polyaryletheretherketone (PEEK) may have various benefits in the production of miniscrews. Finite element analysis (FEA) is a valid and reliable method for calculating stress, strain, and loading forces on complex structures and can be more time- and cost-efficient.

OBJECTIVE: To investigate the biomechanical performance of Ti and PEEK as miniscrew biomaterials employing FEA.

MATERIALS AND METHODS: This study is a 3-D (3D) simulation with FEA. First, 3D miniscrew modeling is done using Ti base material and PEEK (1.4 mm × 6 mm size), as well as 3D inter-radicular space bone modeling. The simulation was performed by modeling the insertion angles (30°, 60°, and 90°) and applying a 200-gram loading force. The biomechanical performance of the miniscrew was then determined using FEA.

RESULTS: As the angle of insertion increases, the tension on the bone decreases, the stress on the TADs increases, and the bone deformation decreases. Compared to TADs made of Ti and PEEK, TADs made of PEEK alone cause more bone stress than TADs made of Ti. The distortion in the maxilla is observed to be larger than in the mandibular.

CONCLUSION: PEEK has greater stress on the bones than Ti and may be prospected as an alternative biomaterial for TAD fabrication, as documented in the FEA.

Keywords:

Dentistry, medicine, orthodontics, polyaryletheretherketone, temporary anchorage device, titanium

Introduction

Malocclusion is a frequent oral ailment that entails an uneven tooth arrangement and an unattractive facial profile. Malocclusion varies from other medical and dental disorders because it is more of a dental issue than a dental illness. This scenario can result in trouble biting or chewing, difficulty speaking, poor tooth brushing, and an increased risk of cavities and periodontal disease.[1] Malocclusion is Indonesia's third most common condition behind caries and periodontal disease. In

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2015–2016, at the Dental Hospital Airlangga University, the prevalence of skeletal class I malocclusion was 43.4%, 36.7% for skeletal class II malocclusion, and 19.7% for skeletal class III malocclusion.[2] Treatment of difficult malocclusion situations, such as patients with skeletal anomalies, patients with massive overjet, and overbite instances where group tooth movement is required, frequently requires more anchoring so that tooth movement can be more flexible without the danger of losing anchorage. Orthodontic knowledge that is still evolving can assist practitioners in providing patients with several treatment alternatives.[3]

Anchorage control is an essential factor in the success of orthodontic treatment. Extra-oral devices often require patient cooperation and are difficult for the clinician to control. This can cause a loss of anchorage so that inter- and intra-arch tooth alignment is not achieved. Intra-oral devices such as the transpalatal arch, lingual arch, Nance's holding arch, and lip bumper do not require patient cooperation; however, intra-oral devices cannot provide absolute anchorage in three planes. These conventional gear anchorages are insufficient and less effective at delivering absolute anchorage. Absolute anchorage is required to prevent movement of the anchorage teeth. This absolute anchorage can only be achieved with ankylosed teeth or dental miniscrews.[4-6]

A temporary anchoring device (TAD) is a bone-attached device that improves anchoring by supporting anchor teeth or decreasing anchorage unit requirements.[7] TADs are known to produce a more free-shifting effect in all directions and a more extensive range of teeth that may be shifted. This is because TADs may provide total anchoring in orthodontic therapy, making it a viable choice for addressing complicated situations. The most frequently used form of TAD is the miniscrew. The benefits of utilizing a miniscrew include its ease of use, lack of need for patient participation, good biocompatibility, resistance to orthodontic pressures, and compact size, allowing it to be utilized in patients of various ages.[8]

Titanium (Ti) is a fundamental material used in the manufacture of miniscrews. Ti offers excellent corrosion resistance, biocompatibility, and mechanical qualities.[9] On the other hand, Ti has various flaws, including micro-movement of the miniscrew, cyclic loading, and an acidic oral environment, which can produce a permanent release of oxide on the surface of the miniscrew, exposing the metal to the electrolyte in the oral cavity. Ti ion and metallic ion release can cause a type IV immune response.[10] Furthermore, Ti has a substantially greater Young's modulus (110 GPa) than bone (14 GPa), and this large discrepancy might be a risk factor for miniscrew failure due to poor stress shielding, resulting in bone resorption and miniscrew fracture.[11]

When exposed to light radiation, miniscrew metal induces light scattering, which is detrimental to tissues.[12] This drives research into alternative miniscrew materials projected to outperform Ti in terms of strength, biocompatibility, and oral cavity stability. Polyetheretherketone (PEEK) is a synthetic thermoplastic polymer that was developed in 1978. PEEK has a Young's modulus between cancellous and cortical bones, reducing mechanical mismatch and stress shielding between bone tissue and miniscrew. PEEK is chemically resistant, has strong mechanical qualities, is biocompatible, has a tooth-like hue that makes it more visually pleasing, and is heat- and moisture-resistant, making it acceptable for all sterilizing processes.[13,14]

Although studying stress and strain distribution in the bone *in vivo* will be difficult, finite element analysis (FEA) is a legitimate and accurate approach for computing stress, strain, and loading forces on complicated structures, which is both time- and cost-efficient. Accordingly, this study was carried out to determine biomechanical performance using FEA. This approach can also examine every variable that can impact mechanical qualities, such as length, diameter, miniscrew thread, bone thickness, density, and the amount of force applied, which can be varied. FEA is used to create 3-D (3D) modeling based on the characteristics of each material, which can then be simulated to mimic circumstances in the oral cavity. Thus, the purpose of this research is to identify the outcomes of biomechanical simulations, namely, the stress and strain distribution of PEEK miniscrews. It is envisaged that this study will serve as a foundation for future research on the fabrication of PEEK-based miniscrews.

Materials and Methods

3D models of cylindrical small head-type miniscrew using titanium Dual-Top (Jeil Medical Corp., Korea) and PEEK (ECACOMP PEEK 150 GF30 natural 1015097, Ensinger GmbH, Nufringen, Germany) were made as the foundation material using the ANSYS Workbench 19 Software. The dimension of miniscrew was 1.4 mm diameter and 6 mm length with thread angle and thread pitch as prescribed by the manufacturer (Jeil Medical Corp., Korea).

Furthermore, a 3D finite element bone block modeling was created to depict the inter-radicular gap between the maxilla and mandibular's first and second premolars with cortical and cancellous bones then integrated with miniscrew and was constructed with the same software as the miniscrew models above. An 8 mm × 14 mm × 10 mm bone model was prepared for simulation. Then, input all the miniscrew and bone material parameters from previously published values. A total of 12 bone models were constructed, six each for maxilla and mandible and three each for titanium and PEEK. Following the completion of the 3D modeling, the simulation is performed by simulating the insertion angles (30°, 60°, and 90°) and applying a loading force of 200 grams to the head of the miniscrew to approximate the force required for anterior retraction. The orthodontic force was applied parallel with the occlusal plane. Maximum stress distribution on bone and miniscrew was analyzed using ANSYS Workbench 19 software. So does the maximum displacement of cortical bone too.

Results

Figure 1 depicts the fusion of a 3D-modeled miniscrew and an alveolar bone. The larger the angle of insertion, the greater the stress on the miniscrew. The FEA results for the biomechanical performance stress on the Ti and PEEK miniscrewed bones and strain on the maxilla and mandibula are shown in Tables 1 and 2. In Ti-based TADs compared to PEEK TADs, the stress on the Ti miniscrew is higher [Figure 2a–c]. The larger the angle of insertion, the greater the tension on the maxillary bone [Figure 3a–g]. The larger the angle of insertion, the less stress there is on the mandibular bone. The lower the distortion of the miniscrew, the larger the insertion angle. Compared to miniscrews composed of Ti and PEEK, Ti miniscrews deform somewhat more than PEEK miniscrews [Figure 4a–g].

Discussion

When the mini-implant is put into the bone model and force is applied, FEA is utilized to mimic the state of the peri-implant bone. This research aims to see if PEEK miniscrews can replace Ti-based miniscrews. This analysis is a simulation utilizing FEA that involves creating a 3D model of a miniscrew made of Ti and PEEK that has been tweaked for material characteristics; then inserting it at angles of 30°, 60°, and 90°; and applying a loading force of 200 grams to approximate anterior en-masse orthodontic retraction. A material with a safety factor greater than 1 is considered mechanically safe. If the safety factor is less than 1, this indicates that the material and its support are in danger of fracture.[15] When the safety factor is less than 1, there is a danger of implant or bone fracture. It is envisaged that the safety factor would be more than 1 to identify alternative miniscrew base materials. The safety factor is a tool for preventing dangers induced by mechanical failure.[16] The best miniscrew design is one that considers the safety element of the base material. This can reduce the likelihood of future failure.[17]

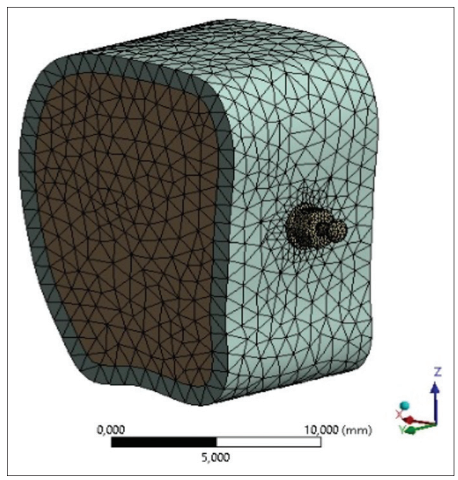

Figure 1: Meshing of 3D modeling miniscrew and bone

Table 1: Simulation results using FEA examine the biomechanical performance stress on the titanium and PEEK TAD bones and strain on the maxilla

Materials	Insertion Angle	Stress on implant (MPa)	Stress on bone (MPa)	TAD deformation (mm)
Titanium	30	34.755	11.659	0.003339
	60	35.378	5.9394	0.002204
	90	36.927	5.1663	0.001868
PEEK	30	36.984	31.272	0.068809
	60	37.827	21.467	0.048154
	90	39.209	20.658	0.040703

Table 2: Simulation results using FEA examine the biomechanical performance stress on the titanium and PEEK TAD bones and strain on the mandibula

Materials	Insertion Angle	Stress on implant (MPa)	Stress on bone (MPa)	Implant deformation (mm)
Titanium	30	34.755	14.112	0.002995
	60	35.378	5.5235	0.001946
	90	36.927	4.5064	0.001662
PEEK	30	36.984	42.224	0.068149
	60	37.827	26.607	0.047429
	90	39.209	23.216	0.040137

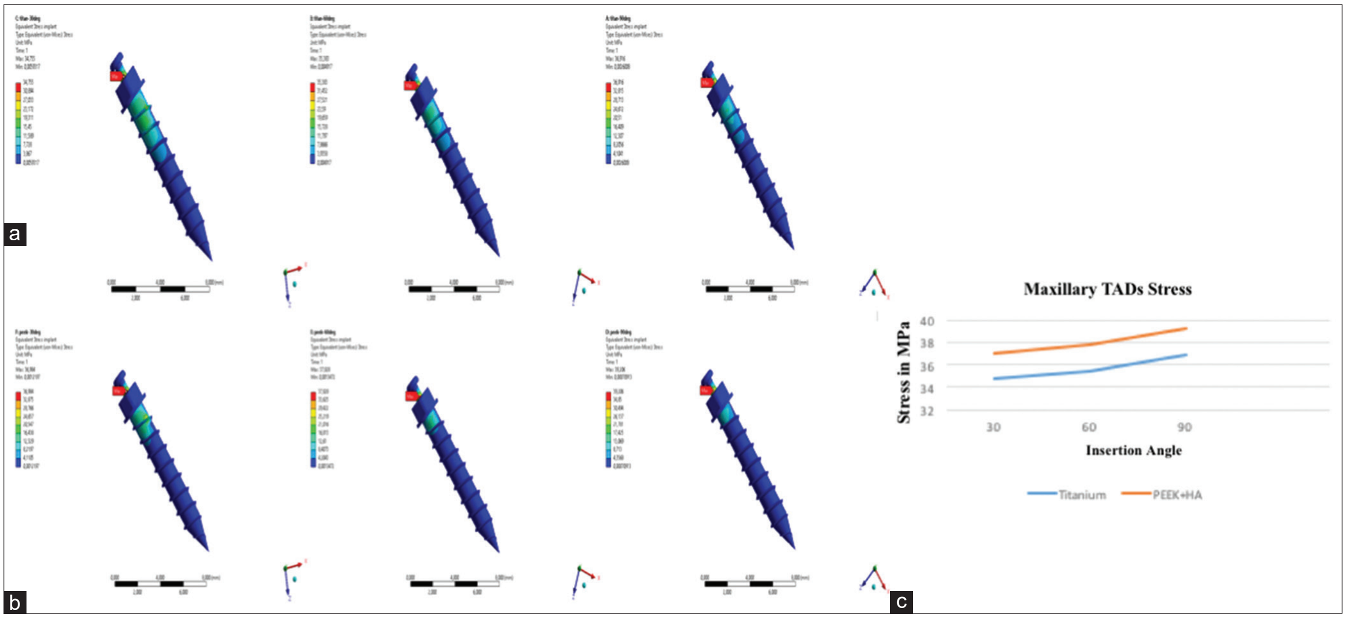

Figure 2: Maxillary miniscrew stress simulation results on miniscrews made from (a) titanium and (b) PEEK with 30°, 60°, and 90° insertion angles (from left to right). (c) maxillary TAD stress simulation results

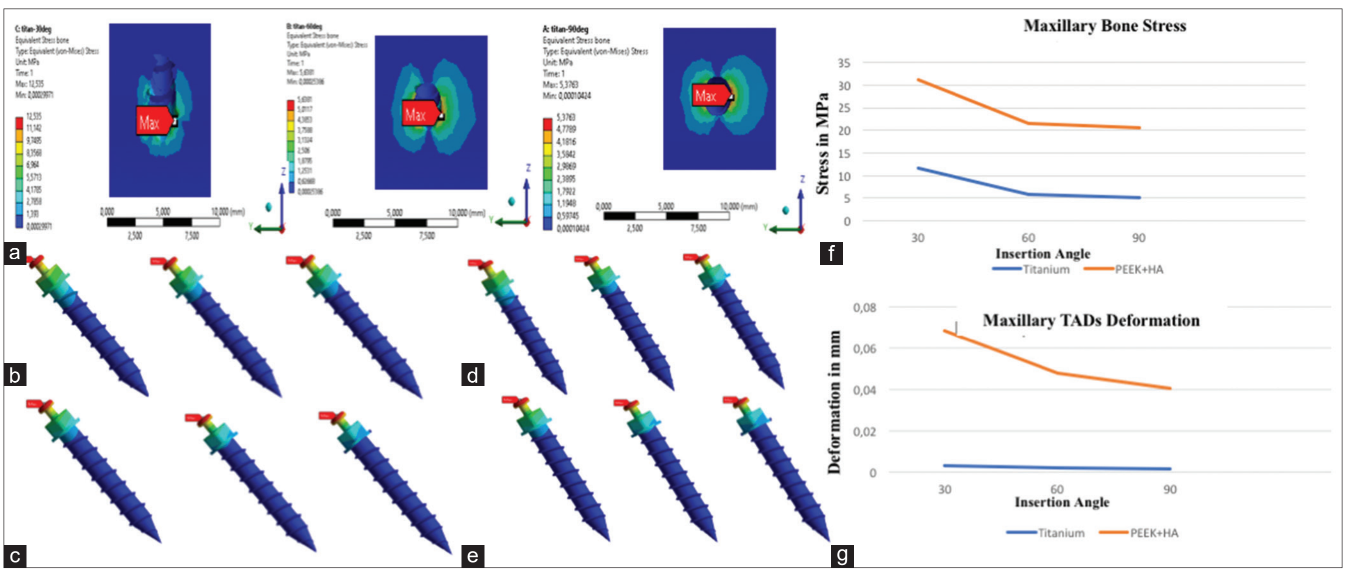

Figure 3: (a) Image of simulated stress on the maxillary bone with miniscrews made of titanium (Ti) and 30°, 60°, and 90° insertion angles. Image of simulated stress on the maxillary bone on miniscrews made of Ti (b) and PEEK (c). Image of simulated deformation of Ti TADs (d) and PEEKs (e) on the maxillary. Result of stress simulation results on the maxillary bone (f) and miniscrew deformation simulation results on the maxilla (g)

The safety factor for the PEEK material is 2.37, obtained by dividing the yield strength value by the maximum von Mises value. The stress derived from the simulation results was 93/39.209. Ti has a safety factor of 2.75. Because the safety factor is greater than 1, it may be deduced that PEEK can be used to make TADs. In this work, two sets of simulations were used to assess the biomechanical performance of Ti and PEEK TADs on the maxilla and mandible. Simulations were run with insertion angles of 30°, 60°, and 90° degrees. According to the data, the larger the angle of insertion, the greater the stress on the TADs. The stress value in the maxilla rose with Ti material (34.755; 35.378; 36.927); with PEEK material, the stress value also rose (36.000; 37.827; 39.209). In the mandibular, Ti is valued at 34.755, 35.382, and 36.925, while PEEK is assessed at 36.984, 37.829, and 39.206. This might be due to the extended lever arm at the 30° insertion angle. This larger lever arm can also diminish the TAD's anchoring resistance, resulting in its failure.[18]

The amount of tension on the bone and the miniscrew is affected by the angle of insertion. Although the angles of insertion differ, the pattern of stress distribution is

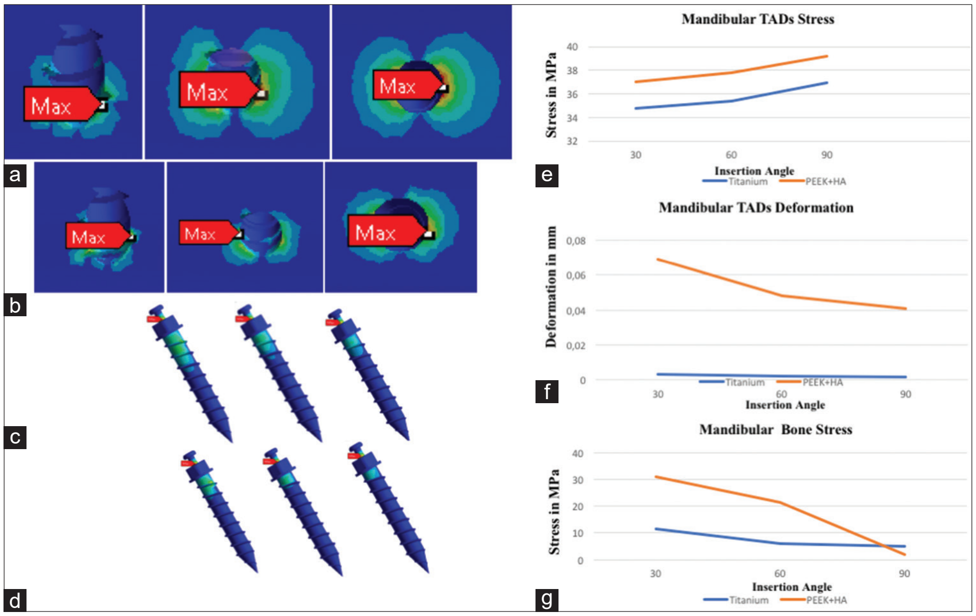

Figure 4: Image of simulated stress on the mandibular bone with miniscrews made of titanium (Ti) (a) and PEEK (b). Images of stress simulation results on a Ti-based miniscrew (c) and PEEK (d) in the mandibular bone. The result of stress simulation results on the miniscrew (e), maxillary bone (f), and TAD deformation simulation results on the mandibular bones (g)

similar between the angles of 30°, 60°, and 90°, namely, concentrated in the neck and first thread areas from the mesial direction, allowing the miniscrew to be inserted vertically at 90° on the buccal side of the bone.[19] As the miniscrew's insertion angle rose, the tension on the bone reduced. This is in line with the previous findings, which discovered that raising the angle of insertion to 30°, 60°, and 90° reduces stress on the bones. The stress value in the maxilla with Ti material is 11.659, 5.9394, and 5.1663; with PEEK material, it is 31.272, 21.467, and 20.658. Ti material in the mandibular had stress values of 14.112, 5.5235, and 4.5064 and 42.224, 26.607, and 23.216 with PEEK + hydroxyapatite material. Because of the lower insertion angle, there is less tension on the bone, and some segments of the thread are not supported by cortical bone. Furthermore, buccal TADs have less cortical bone contact than palatal or lingual TADs.[20,21]

Compared to TADs made of TI and PEEK, the stress on the bones with TADs made of PEEK is greater. For example, the maximum stress for Ti is 31.272, while the maximum stress for PEEK is 11.659. This is because PEEK has a significantly lower elastic modulus than Ti. The higher the elastic modulus, the smaller the deformation since the higher the elastic modulus, the more stress can be transmitted to the surrounding tissue.[22] Bone also contains piezoelectric properties, which means that any force applied to the bone is transferred to the surrounding tissue. This property is often called the piezoelectric effect. Bone may also generate a reverse piezoelectric effect, which means that if a force is applied, the bone can compress itself, allowing it to repair itself more quickly.[23]

The greatest deformation of Ti in this sample was 0.003339 mm, whereas PEEK had a maximum deformation of 0.068809 mm. Previous research has shown that materials with a lower elastic modulus or even one that approaches bone do not preserve peri-implant bone tissue from stress or micro-movement.[24] The results for bone deformations in the maxilla and mandibular revealed that the larger the angle of insertion, the smaller the deformation of the bones and that the deformation was bigger in the maxilla than in the mandibular. This is because the modulus of elasticity in the cortical bones of the maxilla and mandible differs. Because the mandibular cortical bone is thicker than the maxilla, bone stress is greater in the mandibular.[25]

Only one TAD design was used in this investigation, which was 6 mm long and 1.4 mm in diameter. In practice, the bigger the surface of the TADs supported by bone, the narrower the angle of insertion. However, in this study, it was demonstrated that the tension is the highest on the neck and first thread of the TADs, such that with an angle of 90°, the stress may be transferred uniformly, increasing the danger of fracture. As a result, it can be stated that the insertion angle should be greater than 30° and less than 90° for more optimal clinical applications with little risk of implant and bone fracture. According to earlier studies, the ideal angle for miniscrew insertion is 60°–70°.[12] This study's findings backed up prior research, which found that the best angle for insertion is 45°. This is because the miniscrews supported by cortical bone have a larger surface area with a smaller angle, and if the surfaces between the two roots are close together, insertion with a smaller angle is more helpful since it reduces the likelihood of root contact.[26,27] This study result is limited to the biomechanical simulation of Ti miniscrew and PEEK miniscrew insertion angles by means of FEA. Thus, *in vitro* and *in vivo* examination with various methods or a randomized multi-center clinical trial should be done to elucidate the prospect of PEEK as a biomaterial for PEEK fabrication.

Conclusion

PEEK can be used as an alternative foundation material for miniscrew fabrication. The mandibular is more stretched and deformed than the maxilla in the presence of thicker cortical bone. The elastic modulus of PEEK TADs is less than or near to that of bone, yet the stress and deformation are larger than those of the Ti miniscrew. The ideal insertion angle is above 30° and below 90° so that the TADs supported by the bone have a wider surface and the stress on the TADs is not too great, reducing the likelihood of TAD and bone fractures.

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Ethical policy and Institutional Review board statement

Health Committee research Faculty of Dental Medicine, Universitas Airlangga, Surabaya, Indonesia approved the study protocol.

Patient declaration of consent statement

The patients confirmed and agree to participate the study by filled written informed consent and written informed to consent form.

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Conflicts of interest

There are no conflicts of interest.

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