DEFORMATION OF PEEK AND COCR U-SHAPED PALATAL MAJOR CONNECTORS IN DISTAL-EXTENSION REMOVABLE PARTIAL DENTURE: A FINITE ELEMENT ANALYSIS

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ABSTRACT
This study investigated the deformation of major connectors of maxillary bilateral distal-extension removable partial denture (RPD) constructed with cobalt-chromium (CoCr) alloy and polyetheretherketone (PEEK). A three-dimensional maxilla model of a Kennedy Class I was developed from a patient's cone beam computed tomography (CBCT). Two RPDs featuring identical U-shaped palatal major connector designs were fabricated with computer-aided design (CAD) software (SolidWorks 2017; SolidWorks Corp). The CoCr RPD framework had a uniform thickness of 1 mm, while the PEEK RPD framework was thickened to 2 mm. A total bilateral occlusal load of 320 N was applied to the posterior artificial teeth. The deformation of each framework was analyzed along the vertical (Z-axis), anteroposterior (Y-axis), and buccolingual (X-axis) directions by ANSYS Workbench software (ANSYS Workbench 2020; ANSYS Inc.). The PEEK RPD framework exhibited greater overall deformation than the CoCr RPD framework under the same occlusal load. For both materials, the maximum deformation occurred in the vertical direction (Z-axis), where the PEEK framework displaced 0.0128 mm compared to 0.0082 mm for the CoCr framework. Anteroposterior (Y-axis) deformation was also greater for PEEK. The deformation in the buccolingual direction (X-axis) was nearly identical for both materials. To conclude, the lower Young's modulus of PEEK results in greater flexibility and vertical displacement, suggesting a higher potential for transmitting occlusal forces to the underlying residual ridge mucosa. Conversely, the rigid CoCr framework provided broader force distribution.
Keywords: Deformation, Removable Partial Denture, Polyetheretherketone, Cobalt-Chromium Alloy, Major Connector

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INTRODUCTION

Nowadays, removable partial dentures (RPDs) remain one of the significant treatment options in prosthodontics for partially edentulous patients, as they provide for the restoration of masticatory function, aesthetics, and phonetics (Bural, 2016). Among the various partially edentulous arch types, the Kennedy Class I, characterized by bilateral distal-extension edentulous areas, presents significant biomechanical challenges in RPD design, as the prostheses derive their support from a combination of oral structures, including abutment teeth and the mucosa overlying the residual ridges (Nagayama et al., 2020). Moreover, proper RPD design is crucial for achieving adequate support, stability, and retention, all of which are vital for enhancing masticatory efficiency, ensuring long-term success, and preserving the health of the remaining oral structures (Campbell et al., 2017).

A critical component of RPD is the major connector, which must provide rigidity to effectively distribute functional loads across the dental arch, thereby preventing the transmission of damaging torquing forces to the abutment teeth and residual ridge mucosa (Ben-Ur et al., 1989, 1999). Among the various designs for maxillary major connectors, the U-shaped palatal major connector is often employed, particularly in cases with a prominent palatal torus or a patient's strong gag reflex. However, this design is less rigid compared to designs incorporating a posterior palatal strap, making it more susceptible to flexure under occlusal loading (Green & Hondrum, 2003; MM, 2017). This characteristic places even greater emphasis on the choice of RPD framework material to achieve the requisite stability.

Generally, cobalt-chromium (CoCr) alloys have been the conventional material of choice for RPD frameworks due to their high modulus of elasticity, which imparts excellent rigidity and strength even in thin sections (Al Jabbari, 2014). Despite these mechanical advantages, CoCr frameworks are associated with several drawbacks, including potential for metallic taste, metal allergies, and suboptimal aesthetics due to the visibility of metal clasps (Grosgogeat et al., 2022). These limitations have driven the search for alternative materials.

In recent years, high-performance polymers have emerged as promising metal-free alternatives in prosthodontics. Among these, polyetheretherketone (PEEK) has been introduced as a viable material choice for RPD fabrication. PEEK offers a compelling combination of excellent biocompatibility, a tooth-colored appearance, low density, and shock-absorbing qualities (Abdul Hamid et al., 2024; Papathanasiou et al., 2020). Furthermore, case studies have reported high patient satisfaction with RPDs fabricated from PEEK (Curinga et al., 2023; Harb et al., 2019; Zoidis et al., 2016). However, a fundamental difference lies in its mechanical properties, i.e., PEEK has a lower modulus of elasticity, making it substantially more flexible than CoCr. This inherent flexibility raises critical questions about its suitability for distal-extension RPDs, particularly when used with a less rigid major connector design, such as the U-shaped palatal connector. The potential for increased framework deformation under load could alter stress distribution, possibly leading to greater pressure on the residual ridge mucosa and compromised stability (Papathanasiou et al., 2020; Srivastava et al., 2025). Therefore, this study aimed to compare the deformation of maxillary RPD frameworks designed for bilateral distal-extension situations with a U-shaped palatal connector, fabricated from both CoCr and PEEK. The investigation was conducted using Finite Element Analysis (FEA), a validated computational tool for simulating biomechanical behavior and predicting stress and deformation patterns in complex dental structures.

LITERATURE REVIEWS

Types of Maxillary Major Connectors in Removable Partial Denture

The maxillary major connector is a fundamental component of RPD, which provides unification and rigidity to the prosthesis while distributing functional forces across the arch. The selection of a specific design depends on the clinical situation, including the Kennedy classification, the presence of anatomical features like a palatal torus, and the need for support and stability (MM, 2017). Several designs are available, each with distinct biomechanical properties and indications. The palatal bar, often a bulky connector, is typically used in short-span Kennedy Class III applications. Its limited anteroposterior width provides minimal support from the palate, and the bulk required for rigidity can lead to patient discomfort, making it a less popular choice in modern prosthodontics. In contrast, the palatal strap, a wide (at least 8 mm) and thin band, is widely used due to its ability to achieve rigidity without excessive bulk. This design allows for effective stress distribution over a broad palatal area, enhancing both support and patient comfort (Polychronakis et al., 2013).

For patients with an inoperable palatal torus, two primary designs are considered. The anteroposterior palatal bar consists of two bars joined by longitudinal connectors, creating an L-beam effect for rigidity while minimizing tissue coverage. However, its components can feel bulky, and it offers limited palatal support. Another alternative is the anteroposterior palatal strap, which also encircles the torus but uses wider, flatter straps to provide superior rigidity and support, though the presence of multiple straps may be noted by the patient (Green & Hondrum, 2003). The horseshoe or U-shaped connector is another option often used when replacing anterior teeth or in the presence of a torus. However, this design is known to be flexible under occlusal loads. This lack of rigidity makes it a poor choice for distal-extension cases (Kennedy Class I and II), as it fails to provide adequate cross-arch stabilization and may transmit harmful forces to the abutment teeth (Ben-Ur et al., 1999). For cases demanding maximum support and rigidity, such as those with long distal-extension spans or periodontally compromised abutments, the complete palatal plate is the connector of choice. It offers maximal tissue coverage, ensuring the broadest possible stress distribution and excellent rigidity. While biomechanically superior, the extensive palatal coverage may be a source of discomfort for some patients. The clinical decision, therefore, requires a careful balance between the need for biomechanical stability, anatomical constraints, and patient comfort (MM, 2017).

Material Fabrication in Removable Partial Denture

One of the keys to success in RPD treatment depends on choosing the correct material. For a long time, metal alloys were the primary option, but recently, advances have led to the development of many high-performance polymers that can also be used.

1) Cobalt-Chromium Alloy (CoCr)

For decades, CoCr alloy has been the standard material for RPD frameworks. As a base-metal alloy, it offers a desirable combination of adequate physico-mechanical properties and relatively low cost, which has led to its widespread adoption globally. Its primary advantages include high strength, resistance to heat, wear, and corrosion, and generally excellent biocompatibility. For these reasons, CoCr is also utilized for implant frameworks and as a substructure for porcelain-fused-to-metal restorations. It is often preferred over nickel-chromium (NiCr) alloys due to concerns regarding the potential toxic effects of nickel in the oral environment (Al Jabbari, 2014). Despite its long history of successful use, CoCr has several inherent disadvantages. The material's high density results in a heavier prosthesis compared to non-metal alternatives. A significant drawback is the aesthetic compromise caused by the display of metal clasps, which is often unacceptable to patients with high aesthetic demands. Furthermore, a subset of patients may experience allergic reactions to the metallic components (Al Jabbari, 2014; Grosgogeat et al., 2022).

2) Polymethyl Methacrylate (PMMA)

PMMA is a ubiquitous material in dentistry, used for everything from denture bases to temporary crowns. It offers good aesthetics, biocompatibility, and ease of use. However, its suitability as a framework material is limited by significant mechanical weaknesses. PMMA is prone to polymerization shrinkage and possesses low flexural, impact, and fatigue strength, making it susceptible to fracture under functional loads. Attempts to improve its properties often involve reinforcement with metal wires or plates (Alqutaibi et al., 2023).

3) Polyetheretherketone (PEEK)

PEEK is a high-performance, semi-crystalline thermoplastic polymer that has become a prominent metal-free material in dentistry. Initially developed for industrial applications in the late 1970s, it was adapted for medical use in the 1990s. Its application in removable prosthodontics is driven by a unique combination of desirable properties that address the limitations of traditional metal alloys like CoCr (Papathanasiou et al., 2020). PEEK's advantages include its excellent biocompatibility, making it a suitable alternative for patients with allergies to dental alloys. Its tooth-colored appearance offers a significant aesthetic improvement over the metallic display of conventional clasps. Furthermore, its low density (1.3 g/cm^3) results in lightweight prostheses, enhancing patient comfort. A key biomechanical feature is its Young's modulus (3-4 GPa), which closely mimics that of human bone and dentin. PEEK also demonstrates high thermal and chemical stability, low water absorption, and low plaque affinity, contributing to its durability and oral hygiene. Its properties can be further enhanced through surface modifications or by creating composites with bioactive materials like hydroxyapatite (Abdul Hamid et al., 2024; Alqutaibi et al., 2023). Despite its benefits, the clinical application of PEEK requires careful consideration. FEA has shown that PEEK frameworks can reduce stress on abutment teeth, making them potentially advantageous for patients with compromised periodontal support. However, these frameworks may also transfer higher functional stresses to the underlying mucosa on distal-extension ridges. The study also indicated that the material's inherent strength and rigidity may be insufficient for certain high-stress applications, such as maxillary major connectors, when compared to CoCr (Chen et al., 2019). The design and fabrication of PEEK components are critical for success. While PEEK clasps inherently exhibit lower retentive force than metal clasps, this can be compensated for with design modifications, such as increased thickness and specific undercut engagement (Tannous et al., 2012). Modern fabrication methods, particularly CAD/CAM milling of PEEK blanks, have proven highly effective, producing frameworks with superior precision and fit compared to those made with conventional casting techniques (Papathanasiou et al., 2020).

RESEARCH METHODOLOGY

In this study, a three-dimensional model of a Kennedy Class I maxilla, representing a bilateral distal-extension edentulous area, was developed from a patient's cone beam computed tomography (CBCT) obtained from the Faculty of Dentistry at Khon Kaen University. The research protocol was approved by the Center for Ethics in Human Research at Khon Kaen University (Ref: HE662011).

This virtual maxillary model, constructed with computer-aided design (CAD) software (SolidWorks 2017; SolidWorks Corp), included several anatomical components: six maxillary anterior teeth with cingulum rests on the right and left canines, a 0.2 mm thick periodontal ligament (PDL), a 2 mm thick palatal mucosa, and alveolar bone. Two RPDs were designed for a maxillary model to compare two framework materials, as shown in Figure 1. Both RPDs shared an identical design, which included a U-shaped palatal major connector, I-bar clasps on both canines, and an acrylic base with artificial teeth. The key differences were the material and framework thickness. The conventional framework was fabricated from CoCr alloy with a uniform major connector thickness of 1 mm. In contrast, the alternative framework was fabricated from PEEK, and its major connector thickness was increased to 2 mm. The major connector for both designs consisted of an 18 mm anterior band and an 8 mm posterior band (Figure 1).

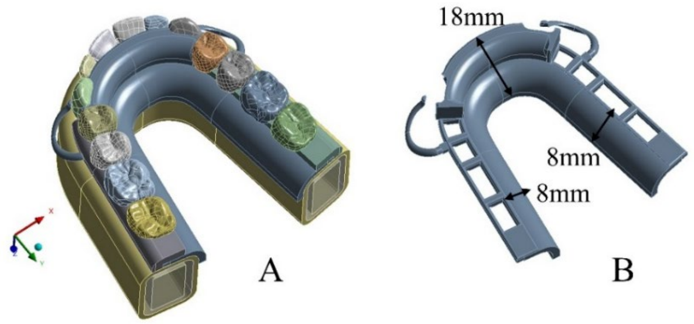

Figure 1 RPD design for both CoCr and PEEK models, shown from the occlusal aspect. (A) Overall RPD design. (B) RPD framework. The models shared an identical design, differing only in framework thickness, which was 1 mm for the CoCr RPD and 2 mm for the PEEK RPD

All materials within the models were assumed to have homogenous, isotropic, and linear elastic properties as listed in Table 1.

Table 1 Mechanical properties of components used in the finite element models

Structure	Young's modulus (GPa)	Poisson's ratio
Enamel	41.1	0.35
Dentin	18.6	0.35
Cementum	15.4	0.31
Periodontal ligament	0.05	0.49
Residual ridge mucosa	0.0025	0.40
Cortical bone	11.76	0.25
Cancellous bone	1.47	0.3
Resin acrylic and artificial teeth	2.45	0.3
CoCr alloy	235	0.33
PEEK	4.1	0.4

A total bilateral biting force of 320 N was applied perpendicularly to the occlusal surfaces of all posterior artificial teeth, with the load distributed across defined points as shown in Figure 2. As a boundary condition, the base of the maxillary bone was fixed in all directions. All contact surfaces were simulated as bonded. The models were meshed with a 0.6 mm element size, generating approximately 418,032 and 429,100 elements for the CoCr and PEEK models, respectively.

A simulation analysis was conducted using ANSYS Workbench software (ANSYS Workbench 2020; ANSYS Inc.) to investigate the deformation of the CoCr and PEEK RPD frameworks under vertical loading. Deformation was evaluated along three axes: X, Y, and Z. The magnitude of deformation in each axis was displayed using a color scale. The X, Y, and Z axes represented movement in the buccolingual, anteroposterior, and vertical directions, respectively (Figure 2).

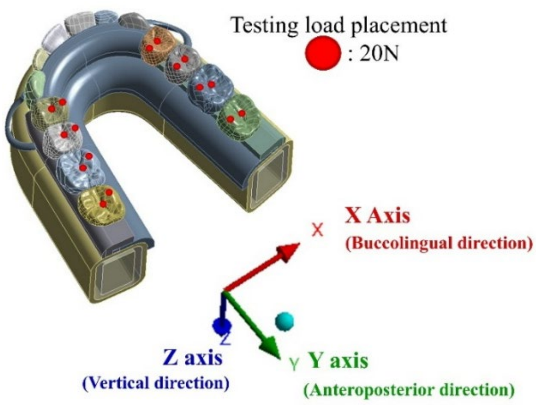

Figure 2 Location of testing load placement on central fossa and palatal cusp of artificial teeth.

RESEARCH RESULTS

In this present study, the biting force was loaded on the posterior artificial teeth and stresses transferred to the distal-extension of RPD, mucosa, abutment and PDL, and the deformation occurred. When comparing RPD constructed from different materials, the deformation of the PEEK RPD was greater than that of the CoCr RPD. Among the three axes, the maximum deformation of the RPD framework occurred on the Z axis (vertical direction), followed by the Y (anteroposterior direction) and X axes (buccolingual direction), respectively. (Figure 3 and 4).

In the X axis, the RPD framework deformation of CoCr and PEEK RPD models were similar (0.0047 mm vs. 0.0049 mm). The posterior sections of the RPD framework, supporting the right and left molars, were deformed lingually.

The RPD framework deformation of CoCr and PEEK RPD models in Y axis were similar (0.0049 mm vs. 0.0063 mm), i.e., framework moved into posterior direction. The maximum deformation of PEEK RPD framework (0.0063 mm) was higher than CoCr (0.0049 mm).

The deformation of RPD framework of CoCr (0.0082 mm) and PEEK RPD models (0.0128 mm.) in the Z axis were similar (0.0082 mm vs. 0.0128 mm), i.e., all parts of the framework were deformed downwardly, except the margin of the anterior part of palatal plate that covering the anterior teeth and tip of the I-bar clasps on both sides, which showed dark blue color indicating deformed upwardly. The maximum deformation of PEEK RPD framework (0.0128 mm) was higher than CoCr (0.0082 mm).

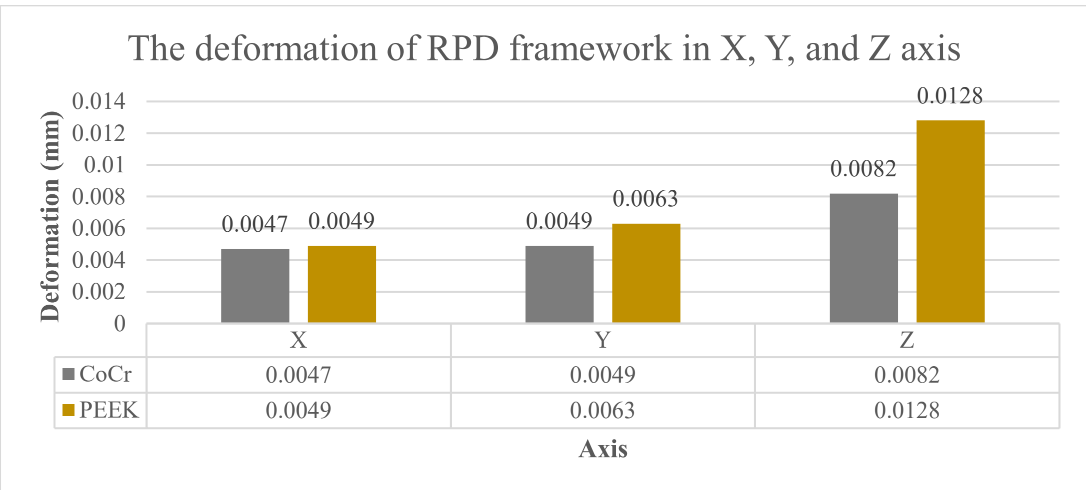

Figure 3 RPD framework deformation of CoCr RPD and PEEK RPD in X, Y, and Z axes in column graph

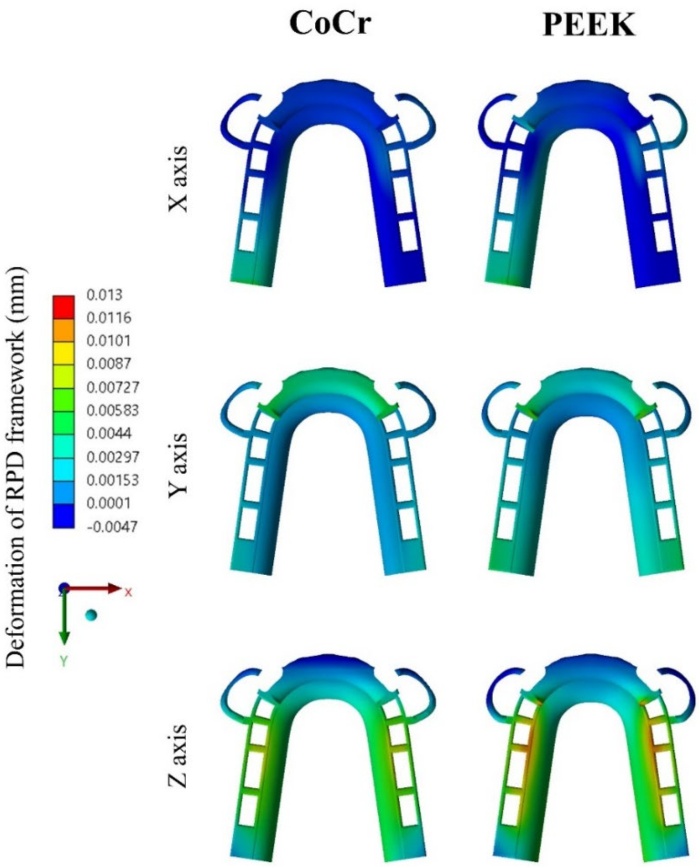

Figure4 RPD framework deformation of CoCr RPD and PEEK RPD in X, Y, and Z axis

DISCUSSION & CONCLUSION

The long-term success of prosthodontic treatment is critically dependent on the proper design of the RPD. For the major connector, rigidity is a fundamental requirement, as it provides the cross-arch stability needed to distribute occlusal forces evenly across all supporting structures (Ben-Ur et al., 1989, 1999; Green & Hondrum, 2003). Framework rigidity, defined as its ability to resist deformation under occlusal load, dictates that a major connector must be maximally rigid to prevent deformation during function (Bhojaraju et al., 2014; Eto et al., 2002). Any significant deformation (such as bending, flexing, or twisting) indicates a failure of the framework to act as a single stable unit, which directly compromises its ability to distribute occlusal forces effectively. Consequently, a lack of this rigidity can lead to pathological conditions, including traumatic damage to the abutment teeth and PDL, injury to the residual ridges, and impingement of the underlying soft tissues (Aridome et al., 2005; Srimaneepong et al., 2004).

This study investigated and compared the deformation characteristics of RPD frameworks constructed from CoCr and PEEK. After applying a biting force to the posterior artificial teeth, the deformation was analyzed along the X, Y, and Z axes. The results showed that the PEEK RPD framework exhibited significantly higher overall deformation than its CoCr counterpart under the same load conditions. This finding is directly attributed to the difference in intrinsic stiffness between the materials, as defined by their Young's modulus. CoCr is a highly rigid alloy (235 GPa), whereas PEEK is a flexible high-performance polymer (4.1 GPa) (Tannous et al., 2012). Therefore, the greater flexibility of PEEK led to larger displacement under load, a finding consistent with previous studies comparing these materials for prosthetic applications (Chen et al., 2019).

Among the three axes, the maximum deformation for both materials occurred along Z axis (vertical direction), followed by Y axis (anteroposterior direction), and finally X axis (buccolingual direction). The highest deformation was observed in the vertical direction in the Z axis (ranged from 0.0082-0.0128 mm), which is expected as the simulated biting force was applied perpendicularly to the occlusal plane. The PEEK RPD displayed more vertical displacement than the CoCr RPD (0.0128 mm vs. 0.0082 mm). In a tooth-tissue supported RPD, this vertical force induces rotation around a fulcrum line passing through the abutment rests (Mousa et al., 2020). The distal extensions are consequently compressed against the resilient mucosa, resulting in downward displacement, while a counter-rotation causes a slight upward lift at the margin of the anterior part of palatal plate covering the anterior teeth and the I-bar clasp tips, as observed in the model.

The greater vertical displacement observed in the distal extension bases of the PEEK RPD is a direct consequence of the material's flexibility. While this flexibility may lead to lower stress accumulation within the framework itself, it implies that a greater portion of the occlusal load is transferred to the underlying residual ridge mucosa. In contrast, the high rigidity of the CoCr framework results in less vertical displacement, providing better support and distributing forces more broadly across the remaining teeth and tissues (Srimaneepong et al., 2004**.** Similarly, a previous FEA study reported that while PEEK RPDs accumulated less internal stress, they exhibited greater vertical displacement of the underlying mucosa compared to CoCr RPDs (Chen et al., 2019). Another study suggested that the potential for increased pressure on soft tissues from flexible denture materials might be one of the contributors to residual ridge resorption over time (Kumar et al., 2021). However, a clinical study by Lucio et al. found no significant short-term differences in residual ridge height between patients with PEEK RPDs and a control group without prostheses over a one-year period (Lo Russo et al., 2022). Thus, further studies on the effects of PEEK RPDs on oral tissues are required.

The deformation in the Y-axis (anteroposterior), which was greater for PEEK RPD (0.0063 mm) than for CoCr RPD (0.0049 mm), might be a secondary effect of the primary vertical load on the sloped anatomy of the residual ridges and palatal vault. As the framework is pressed downward, it also tends to slide posteriorly. The increased flexibility of the PEEK might allow for more pronounced movement in this direction.

The deformation in the X-axis (buccolingual direction) was nearly identical for both materials (0.0049 mm for PEEK vs. 0.0047 mm for CoCr), with the posterior sections of the frameworks moving lingually. This suggests that for the U-shaped major connector design used in this study, the geometry of the framework may be a more dominant factor in resisting buccolingual flexure than the material's modulus of elasticity. U-shaped connectors are known to be less rigid than designs incorporating an anteroposterior palatal strap, and this inherent lack of cross-arch rigidity might explain the similar lingual displacement under load for both materials (Bhojaraju et al., 2014; Eto et al., 2002).

However, this linear FEA study has some limitations. The material properties were assumed to be isotropic, homogeneous, and linearly elastic, which is a simplification of the complex biological reality. The interfaces between components, such as the denture base and mucosa, were modeled as bonded condition, which does not account for the frictional condition that exists clinically (Nakamura et al., 2014). Finally, the simulation only applied vertical occlusal forces, whereas mastication involves complex multidirectional forces that could alter the deformation patterns. Further research is required.

Based on the findings of this linear FEA study, the following conclusions can be drawn:

1) The PEEK RPD exhibited greater overall deformation compared to the CoCr RPD under the same occlusal load, due to its lower Young's modulus and higher flexibility.

2) For both framework materials, the maximum deformation occurred in the vertical direction (Z-axis), followed by the anteroposterior (Y-axis) and buccolingual (X-axis) directions.

3) The greater vertical displacement of the PEEK RPD might suggest a higher potential for transferring occlusal forces to the underlying residual ridge mucosa, whereas the rigid CoCr framework provided broader force distribution.

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