Asian Journal of Periodontics and Orthodontics
2025, Volume 5, Page No: 56-64

Available online at: www.tsdp.net

ISSN: 3062-3499

Original Article

Effects of Orthodontic Force Intensity and Movement Patterns on Lower Premolar Pulp and Neurovascular Bundle: A Finite Element Analysis

Zhaobei Cai[1]*, Chuan Xiang Li[1], Aleda M H Chen[2], Jian Zhou[1], Xiao-Ming Zhang[1]

[1]Department of Orthodontics, Peking University School and Hospital of Stomatology, Beijing, P.R. China.
[2]Division of Paediatric Dentistry and Orthodontics, Faculty of Dentistry, the University of Hong Kong, Hong Kong SAR, China.

***E-mail** ✉ Cai.zhaobei1970@gmail.com

Received: 19 January 2025; **Revised:** 21 April 2025; **Accepted:** 25 April 2025

ABSTRACT

This study used finite element modeling to explore stress on the dental pulp and neuro-vascular bundle (NVB) in second lower premolars. The analysis aimed to determine ischemic and resorptive risks from 2 N and 4 N orthodontic forces applied during rotation, translation, tipping, intrusion, and extrusion in healthy periodontium. Nine 3D models from nine patients were created, resulting in a total of 90 simulations. Both force levels produced similar stress patterns across the five movements, with 4 N approximately doubling stress magnitudes compared to 2 N. The NVB consistently showed the highest stress, but all values remained below the physiological maximum hydrostatic pressure (16–22 KPa). Rotation generated the greatest stress, followed by intrusion and extrusion, while translation produced the lowest. Forces of 2 N and 4 N appear safe for healthy teeth in intact periodontium. Nonetheless, rotation and translation may cause localized stress in the coronal pulp, potentially affecting previously treated teeth (direct or indirect pulp capping). Intrusion and extrusion create higher NVB deformation, which could influence teeth with prior trauma, such as occlusal injuries.

Keywords: Dental pulp, NVB, Ischemic risk, Intact periodontium, Orthodontic forces, Finite element analysis

How to Cite This Article: Cai Z, Li CX, Chen AMH, Zhou J, Zhang XM. Effects of Orthodontic Force Intensity and Movement Patterns on Lower Premolar Pulp and Neurovascular Bundle: A Finite Element Analysis. Asian J Periodont Orthodont. 2025;5:56-64. https://doi.org/10.51847/iWxnonihg6

Introduction

Orthodontic procedures place the dental pulp and neuro-vascular bundle (NVB) at risk of reduced blood flow and ischemic damage, which can lead to pulp necrosis or inflammation. Teeth that have experienced trauma, such as occlusal injuries [1, 2], or prior interventions involving the pulp (e.g., direct or indirect pulp capping) [3–6], have diminished capacity to respond to stress and maintain tissue health.

The periodontal ligament (PDL) serves as the primary shock absorber for forces applied during orthodontic treatment, shielding the pulp and NVB from excessive stress [3–6]. In anatomical terms, the NVB resides in the apical third of the PDL and is directly exposed to mechanical load, whereas the pulp is contained within the pulp chamber and root canals [3–5]. The PDL contains an extensive network of blood vessels that sustain local circulation and metabolism, supporting the ligament itself, the pulp, and adjacent bone [3–5]. Normal physiological pressure in this system ranges from 16 to 22 KPa, representing the maximum hydrostatic pressure (MHP), which approximates 80% of systolic blood pressure [3, 7–10].

In teeth with healthy periodontium, small orthodontic forces induce only limited circulatory changes, sufficient to trigger normal PDL and bone remodeling [4, 11, 12]. However, when applied forces exceed the MHP for prolonged periods, local vessels may collapse, sharply increasing the risk of ischemia and tissue resorption [3, 13, 14]. Accordingly, the type, magnitude, and duration of applied orthodontic forces directly influence the likelihood of circulatory disturbances and degenerative changes in the pulp and NVB [3–5, 15–17]. Teeth or periodontium previously subjected to trauma or injury [15, 17, 18] show structural and functional alterations that heighten susceptibility to ischemic and resorptive events compared with uninjured teeth [3–6, 19–28].

It should be noted that direct observation of the dental pulp and neuro-vascular bundle (NVB) is not possible. Consequently, morphological or functional changes are typically detected only after clinical symptoms, such as pulpitis and related complications, appear [15–35]. Nevertheless, numerical simulations can indirectly assess these tissues by evaluating stress patterns induced by orthodontic forces, allowing estimation of ischemic and resorptive risks [3–5].

Clinical and numerical studies have indicated that light orthodontic forces in the range of 0.5–1 N are generally safe for teeth with intact periodontium [4, 36–39]. However, higher forces have been associated with ischemic responses and regressive tissue changes [11, 12, 40, 41]. The optimal magnitude of orthodontic force remains under debate, highlighting the need for further evidence [3–5]. Many in vivo studies suffer from methodological limitations, emphasizing the importance of new research with robust methodology and clinical correlation focused on stress distribution [12, 30, 40].

Currently, only a limited number of numerical studies directly examine the dental pulp and NVB, some conducted by our group [4, 5, 37–39], whereas more studies target the PDL, particularly its apical third containing the NVB. Yet, most PDL-focused studies have produced inconsistent results due to methodological flaws. Our prior work addressed these issues and proposed a more reliable methodology for accurate stress assessment [4, 5, 37–39, 42–44]. Recent numerical investigations indicate that orthodontic forces from 0.28 to 4 N are tolerated by periodontal tissues without major functional compromise [7, 8, 42, 43, 45], contradicting earlier reports that support exclusively light forces [4, 5, 36–39]. Properly conducted finite element analyses further suggest that the pulp and NVB experience comparatively lower stress even under forces exceeding 1 N.

Despite the advantages of numerical methods in producing precise results, critical factors such as failure criteria, boundary conditions, sample size, and anatomical fidelity must be carefully addressed [3–5, 37–39, 42–44, 46]. Previous studies often overlooked these aspects, leading to results of questionable accuracy, including findings that sometimes contradicted clinical observations or exceeded physiological MHP, even under light forces [7–10, 15–18, 30, 46–62]. However, all current numerical models correctly apply linear elasticity, isotropy, and homogeneity assumptions for dental tissues, as validated by multiple reports [3–5, 37–39, 42–44, 46].

Therefore, to accurately characterize stress distribution in the dental pulp and NVB—structures too small and complex for direct in vivo examination—the most reliable approach remains numerical analysis using 3D models derived from cone-beam computed tomography (CBCT) [3–5, 37–39, 42–43].

This investigation is part of an ongoing stepwise project (clinical protocol 158/02.04.2018) examining the effects of orthodontic forces on dental tissues across various levels of periodontal health [4, 5, 37–44]. Our prior research was the first to point out limitations in the finite element method's accuracy for dental studies and to establish a reliable protocol to overcome these issues.

The present study aims to provide new insights into how larger orthodontic forces affect the dental pulp and neuro-vascular bundle (NVB). Stress distributions generated by 2 N and 4 N forces were simulated during five common orthodontic movements—rotation, translation, tipping, intrusion, and extrusion—in teeth with intact periodontium. Additionally, ischemic and degenerative–resorptive risks were assessed by comparing the simulated stresses with the physiological maximum hydrostatic pressure (MHP).

Materials and Methods

This study evaluated stress in the dental pulp and neuro-vascular bundle (NVB) of teeth with intact periodontium using nine 3D models of the second lower premolar, resulting in 90 simulations. The sample comprised nine patients (four males, five females) with a mean age of 29.81 ± 1.45 years [4, 5, 37–44].

Teeth were selected only if intact, properly aligned, free of prior treatments (endodontics, fillings, crowns), and with minimal bone loss (≤1–2 mm). Adequate oral hygiene and an indication for orthodontic treatment were also required. Teeth were excluded if they had unusual root shapes (e.g., double non-fused roots, extreme curvature), abnormal crowns, temporary teeth, root defects (e.g., external resorption), radiographic bone defects, irregular pulp chambers or canals, bone loss >2 mm, or visible inflammation.

The second lower premolar and its adjacent teeth were scanned with CBCT (ProMax 3DS, Planmeca, Helsinki, Finland) at 0.075 mm voxel size. Manual reconstruction was done using Amira 5.4.0 (Visage Imaging Inc., Andover, MA, USA) due to anatomical complexity. Each tissue—enamel, dentine, dental pulp, NVB, periodontal ligament (PDL), and cortical/trabecular bone—was segmented separately **(Figure 1)**. Cementum was modeled as dentine because of similar physical and imaging properties **(Table 1)**. The PDL's natural thickness (0.15–0.225 mm) was preserved to maintain NVB positioning.

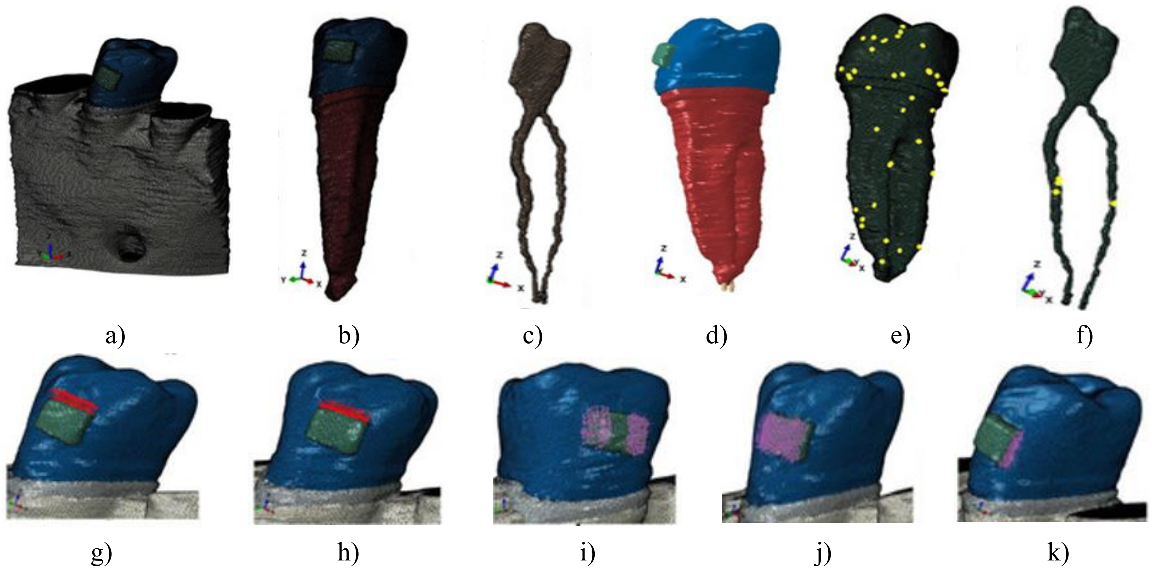


Figure 1. Mesh overview of a single 3D model: a) second lower right premolar with intact periodontium, b) isolated premolar, c) dental pulp and NVB, d) premolar including pulp and NVB, e) premolar mesh with minor warnings, f) pulp/NVB mesh warnings. Force vectors applied: g) extrusion, h) intrusion, i) rotation, j) tipping, k) translation.

Table 1. Material properties.

Material	Elastic Modulus (GPa)	Poisson's Ratio	Sources
Tooth Enamel	80	0.33	[4, 5, 37-39, 42-44]
Dentin/Cementum Layer	18.6	0.31	[4, 5, 37-39, 42-44]
Pulp and Neurovascular Bundle	0.0021	0.45	[4, 5, 37-39, 42-44]
Periodontal Ligament (PDL)	0.0667	0.49	[4, 5, 37-39, 42-44]
Cortical Bone Tissue	14.5	0.323	[4, 5, 37-39, 42-44]
Trabecular Bone Tissue	1.37	0.3	[4, 5, 37-39, 42-44]
Stainless Steel Bracket (Cr-Co Alloy)	218	0.33	[4, 5, 37-39, 42-44]

In all nine models, the second lower premolar was preserved, and missing alveolar bone was rebuilt with trabecular and cortical components to reconstruct intact periodontium. A standardized stainless-steel bracket base was added to the vestibular crown to prevent variations in force application.

Meshes contained 5.06–6.05 million tetrahedral elements (C3D4) and 0.97–1.07 million nodes, with global element sizes from 0.08 to 0.116 mm. Manual reconstruction caused a few warnings: 39 for the tooth (0.00589% of 661,137 elements) and 4 for pulp/NVB (0.0158% of 25,252 elements). All warnings were in non-critical areas, and internal checks confirmed model integrity.

Simulations used Abaqus 6.13–1 (Dassault Systèmes Simulia, Maastricht, Netherlands). The five orthodontic movements—rotation, translation, tipping, intrusion, and extrusion—were applied with 2 N and 4 N forces. Tresca's failure criterion, suitable for ductile-like dental tissues, was employed. Boundary assumptions included encastered bases, perfectly bonded interfaces, linear elasticity, isotropy, and homogeneity.

Stress results were presented as color-coded maps (red–orange: high, yellow–green: moderate, blue: low). Values were compared to physiological maximum hydrostatic pressure (16–22 KPa) to assess ischemic risk in intact periodontium under higher orthodontic loads.

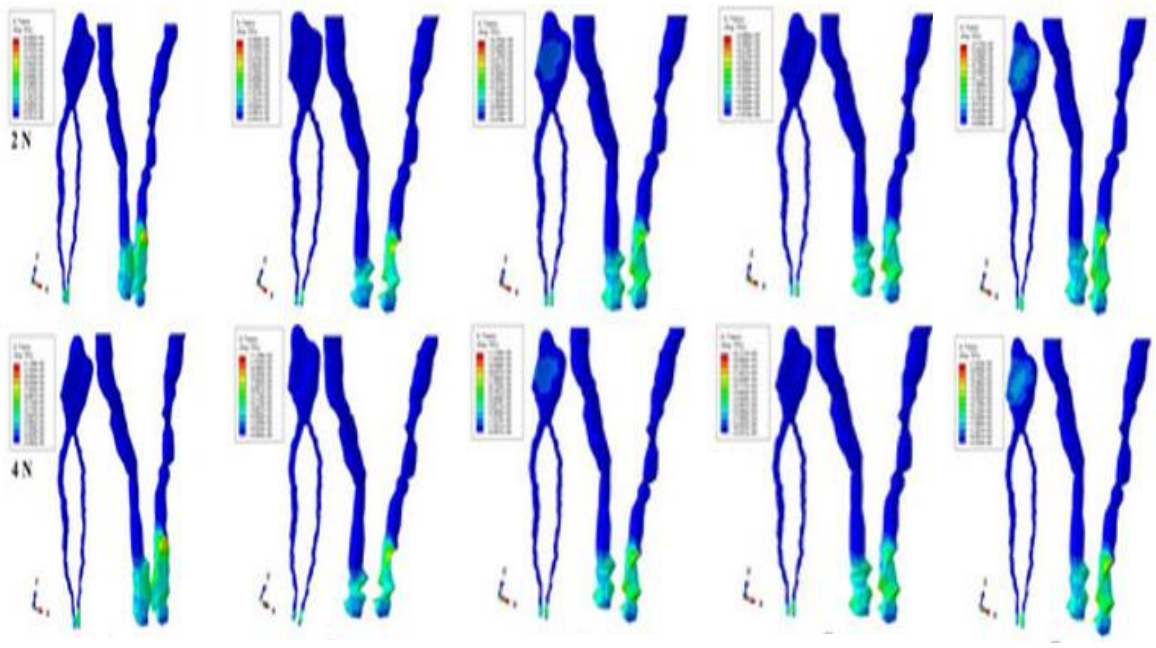
Nine 3D models of second lower premolars with minimal bone loss were reconstructed, preserving each tooth and rebuilding surrounding bone and PDL for intact periodontium. Stainless-steel bracket bases were added on the vestibular crown surfaces to avoid design interference.

Meshes contained 5.06–6.05 million C3D4 tetrahedral elements and 0.97–1.07 million nodes, with element sizes 0.08–0.116 mm. Minor warnings appeared (39 in tooth, 0.00589%; 4 in pulp/NVB, 0.0158%), all in non-critical regions, with no errors.

Simulations used Abaqus 6.13–1, testing rotation, translation, tipping, intrusion, and extrusion under 2 N and 4 N. Tresca criterion was applied, with boundary conditions assuming encastered base, linear elasticity, isotropy, and homogeneity. Stress maps (red–orange high, yellow–green moderate, blue low) were compared with physiological MHP (16–22 KPa) to assess ischemic risk in intact periodontium.

Results and Discussion

Stress was consistently highest in the NVB across all movements and both force levels. The remaining dental pulp showed only minor stress, reflecting protection from the pulp chamber and root canals. Qualitatively, both 2 N and 4 N forces produced similar patterns; quantitatively, 4 N roughly doubled stress levels compared to 2 N **(Figure 2, Table 2)**.



a) b) c) d) e)

Figure 2. Stress comparison under 2 N and 4 N forces for one of the nine 3D models with intact periodontium, showing five orthodontic movements: a) extrusion, b) intrusion, c) rotation, d) tipping, e) translation.

Table 2. Average shear stress values (KPa) recorded in intact periodontium across the nine models under 2 N and 4 N forces.

Force Level	Tissue Type	Rotational Shift (mm)	Lateral Movement (mm)	Angular Deviation (mm)	Upward Displacement (mm)	Downward Displacement (mm)
2 N	Neurovascular Bundle (NVB)	0.57	0.37	0.49	0.57	0.57
	% NVB	1.00	1.00	1.00	1.00	1.00
	Tooth Pulp	0.05	0.03	0.04	0.05	0.05
	% Pulp	1.00	1.00	1.00	1.00	1.00
4 N	Neurovascular Bundle (NVB)	1.15	0.74	0.98	1.14	1.14
	% NVB	1.00	1.00	1.00	1.00	1.00
	Tooth Pulp	0.10	0.07	0.08	0.10	0.10
	% Pulp	1.00	1.00	1.00	1.00	1.00

Abbreviations: NVB = neuro-vascular bundle; % NVB = frequency of stress increase in NVB; Pulp = apical third of dental pulp; % Pulp = frequency of stress increase in pulp.

Across all nine patients **(Table 2)**, stress levels caused by 4 N forces remained below the physiological maximum hydrostatic pressure (16 KPa). This indicates that in healthy premolars with intact periodontium, 4 N does not create ischemic or resorptive risk for the NVB or dental pulp. For example, the NVB under rotational force experienced stress roughly 21.6 times lower than the MHP.

Rotation was the most demanding movement, producing the highest stress, followed by intrusion and extrusion. Tipping and translation caused the lowest stress levels. Color-coded maps **(Figure 2)** show most NVB regions under moderate stress (yellow–green), with only small orange–red zones that could generate localized circulatory disturbances. Overall, average stress values stayed below 16 KPa, suggesting negligible risk for pulp necrosis or tissue resorption.

Coronal pulp stress appeared mainly during rotation and translation, localized on vestibular, mesial, and distal areas **(blue shades in (Figures 2c and 2e))**. Though below MHP, these regions could still experience local circulatory disturbances, particularly in teeth previously treated with pulp capping. Translation appears most likely to provoke pulpal risk, potentially leading to pulpitis. The other three movements had minimal impact on coronal pulp.

Stress in the root canal pulp remained largely unaffected by either movement type or force magnitude. The NVB showed the greatest deformation during intrusion and extrusion **(Figures 2a and 2b)**, suggesting that these movements may pose degenerative or ischemic risks in teeth with prior trauma.

This study, based on ninety numerical simulations of second lower premolars, shows that in healthy intact periodontium, orthodontic forces up to 4 N have minimal impact on the dental pulp and NVB. Quantitatively, the maximum stress in the NVB during rotation—the most demanding movement, followed by intrusion and extrusion—remained roughly twenty-one times below the physiological maximum hydrostatic pressure (MHP), while stress on the dental pulp was even smaller.

These findings are consistent with our earlier investigations using lighter forces under similar conditions, including the same boundary assumptions, movements, and 3D premolar models [4, 5], as well as with other in vivo studies [15–18, 30] and Proffit *et al.* [36]. Previous research from our group highlighted the tooth and PDL's ability to absorb and dissipate loads, showing that only a very small fraction of applied force reaches the NVB and pulp [3–5, 37–39, 42, 43]. Given that the NVB resides in the apical third of the PDL, which acts as the main load buffer, these results are biomechanically sound and agree with clinical observations [3–5, 37–39, 42, 43]. Because the measured stresses **(Table 2)** are below 16 KPa, no ischemic or degenerative–resorptive risk is expected in healthy teeth with intact periodontium. However, the PDL experiences the largest stress, suggesting that further simulations are necessary to examine PDL behavior under higher loads.

If a tooth has previously experienced trauma (e.g., occlusal trauma) [6, 15–28] or pulp injury from dental procedures (direct or indirect pulp capping) [15–35], both the NVB and pulp may be susceptible to ischemic and degenerative–resorptive changes, in agreement with other reports [1, 2]. In such cases, rotation and translation movements can generate localized stress in the coronal pulp—vestibular, mesial, and distal areas **(Figures 2c and 2e)**—potentially causing circulatory disturbances and related tissue risks [6, 19–28]. Intrusion and extrusion, producing greater NVB deformation **(Figures 2a and 2b)**, may also lead to circulatory disturbances, ischemia, and degenerative–resorptive changes, as supported by Minch *et al*. [14] and other studies [15–35].

It is also important to consider that aging itself causes degenerative–resorptive changes in the dental pulp and NVB, which cannot be fully assessed in vivo and may increase ischemic vulnerability under higher forces [1, 15, 18, 29]. Additionally, current dental treatments involving direct or indirect pulp capping can induce local functional and structural changes, affecting long-term tissue response to mechanical loading [1, 6, 15–35].

Rotation produced the greatest stress among the five orthodontic movements, as reported in our previous work [3–5, 37–39, 42, 43], with intrusion and extrusion following closely **(Table 2)**. This finding agrees with Minch *et al*. [14] and Hofman *et al*. [9, 10], who identified intrusion as the movement causing the highest stress in teeth with intact periodontium.

Because dental pulp and NVB are small and anatomically complex, few studies have evaluated their biomechanical behavior during orthodontic procedures. Since the NVB lies in the apical third of the PDL, its mechanical response can be inferred from the PDL. However, most prior numerical models did not accurately include the NVB in the apical PDL [7-10, 45], often resulting in stress values exceeding MHP even under light forces. For example, Hofman *et al*. [9, 10] reported stresses of 80 KPa for 1 N intrusion and 40 KPa for 3–6 N lingual torque, which suggests extensive tissue risks not observed clinically. Wu *et al*. [7, 8, 45] suggested 2.1–2.9 N as optimal for rotational forces on a premolar, with stress below MHP at the PDL apex and negligible stress at the cervical area—an outcome inconsistent with clinical evidence [15–18, 30, 48, 49] and the recommendations of Proffit *et al*.

[36] favoring light forces. By contrast, our models, with higher anatomical fidelity, produce more accurate results compared to previous numerical analyses [9, 10, 15–55].

It is important to note that our simulations used isolated movements, whereas clinical practice often combines motions, which could reduce local stress and the qualitative color-coded distributions. Nevertheless, numerical methods remain the only practical way to assess stress in these intricate structures, as in vivo approaches cannot provide detailed regional data.

Finally, several methodological factors directly influence numerical accuracy, including choice of failure criteria, boundary conditions, anatomical detail, and sample size [9–55]. Failure to account for these factors represents a major limitation in computational analyses of dental tissues.

The selection of failure criteria depends on the material type and is considered essential for obtaining precise results [46]. Our previous studies [3–5, 37–39, 42, 43] highlighted that dental tissues behave similarly to ductile materials, making the Tresca criterion appropriate for accurate numerical analyses. In contrast, many prior studies [9, 10, 15–18, 30, 47–55] overlooked this requirement, which, as our work has shown, can lead to notable inaccuracies [3–5, 37–39, 42, 43].

Boundary conditions, particularly isotropy, linear elasticity, and homogeneity, are commonly assumed in numerical models, even though living tissues are anisotropic and non-linear. Nevertheless, our earlier work confirmed that such assumptions remain valid for forces up to 2.4 N when the Tresca criterion is applied, as small loads produce minimal tissue displacement, satisfying linear elasticity requirements [3–5, 37–39, 42, 43].

The anatomical precision of the 3D models depends heavily on the mesh density and node count. Our models contained 6.05 million tetrahedral elements and 1.07 million nodes, with global element sizes ranging from 0.08–0.116 mm—significantly higher than previous studies [9, 10, 15–55], which used 40–12,731 times fewer elements and 4.4–1463 times fewer nodes. Furthermore, our models were reconstructed from CBCT images rather than simplified idealized geometries, and we included a larger sample size of nine models compared with the single-model designs commonly used.

We selected the mandibular premolar region because most numerical analyses have focused on molars and incisors, leaving premolars underrepresented despite their functional role in occlusion and load distribution. Traditional engineering approaches for numerical studies typically rely on a single model, which is sufficient to explore varying experimental conditions [5, 7, 8, 38, 39, 46, 56–59, 62]. However, to improve accuracy and reliability, our study employed nine models and a total of ninety simulations.

By following these essential criteria—including proper failure criteria, boundary assumptions, anatomical accuracy, and adequate sample size—our numerical analysis achieved high reliability for dental tissue behavior, comparable to engineering standards. Nonetheless, numerical simulations cannot replicate all clinical conditions; thus, results must be validated against clinical data, such as the MHP, and interpreted in the context of clinical knowledge. Future investigations should evaluate the impact of larger orthodontic forces on dental tissues during periodontal breakdown, using the same methodology to assess potential ischemic and resorptive risks.

Conclusion

1. In an intact periodontium, stress patterns under 2 N and 4 N forces were comparable across the five orthodontic movements, but the intensity doubled for 4 N, with the NVB consistently experiencing the highest stress.
2. Stress induced by both forces remained under the physiological maximum hydrostatic pressure (MHP), suggesting no ischemic or degenerative–resorptive risk in healthy, untreated teeth.
3. Among the movements, rotation produced the greatest stress, closely followed by intrusion and extrusion; translation caused the least.
4. Rotation and translation caused localized stress in the coronal pulp (vestibular and proximal regions), which may pose risks in teeth previously treated with direct or indirect pulp capping.
5. Intrusion and extrusion led to greater NVB deformation, indicating that teeth with prior trauma (e.g., occlusal injury) might experience circulatory disruption, ischemia, or resorptive/degenerative effects.

Practical implications

Research on the biomechanical response of the dental pulp is limited, and NVB behavior during orthodontic movements has not been previously studied. This study provides the first detailed assessment of stress distribution in both pulp and NVB under forces of 2–4 N in intact periodontium. These findings are clinically relevant for planning orthodontic treatment and evaluating whether applied forces could cause ischemic or resorptive damage. Prior numerical studies did not consider teeth with prior trauma or pulp treatment; our work addresses these gaps and demonstrates that higher orthodontic forces may pose risks under these conditions. From a biomechanical perspective, this study introduces a validated numerical methodology for analyzing pulp and NVB tissues, fulfilling all critical criteria for accurate modeling in dental biomechanics.

Acknowledgments: None

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

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