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Evaluation of Orthodontic Force Magnitude on Root Resorption: A Clinical and Radiographic Study

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ABSTRACT

Objectives: To evaluate the effect of orthodontic force magnitude on external apical root resorption (EARR) using clinical and radiographic outcomes. Materials and Methods: A prospective, parallel-group study was conducted at a university dental hospital in Riyadh, Saudi Arabia. Sixty-six patients were allocated to light (25–50 g), moderate (75–100 g), or heavy (150–200 g) continuous forces delivered by nickel–titanium closed-coil springs for three months. Imaging at baseline (T0) and follow-up (T1) used cone-beam computed tomography when ethically justified or standardized periapical radiographs. The primary endpoint was change in CEJ–apex root length (mm); secondary endpoints included Malmgren index grades, pain scores, and adverse events. Results: Groups were comparable at baseline. Mean EARR (Δ root length, mm ± SD) increased with force: light 0.29 ± 0.18, moderate 0.49 ± 0.24, heavy 0.83 ± 0.31. One-way ANOVA was significant ($F(2,63)=26.43$, $p<0.001$); Bonferroni-adjusted comparisons confirmed heavy > moderate > light (all $p \leq 0.03$). Clinically relevant shortening (≥2.0 mm) occurred in 0%, 4.5%, and 9.1% of participants, respectively. Malmgren grades shifted toward 2–3 with heavier forces. In mixed-effects models, force magnitude was the strongest predictor (βmoderate=+0.19 mm, 95% CI 0.09–0.30; βheavy=+0.52 mm, 95% CI 0.40–0.64), and pointed apical morphology independently increased risk (+0.18 mm, 95% CI 0.07–0.28). Conclusions: Heavier continuous forces substantially increase EARR, while light forces produce minimal, clinically insignificant changes. Treatment should prioritize light to moderate, well-calibrated forces and risk-stratified radiographic monitoring. Clinical Significance: Standardized periapicals suffice for routine surveillance; CBCT should be reserved for equivocal or high-risk cases where three-dimensional assessment will alter management.

KEYWORDS: Orthodontic force magnitude; External apical root resorption; Cone-beam computed tomography; Malmgren index; Nickel–titanium coil springs; Periodontal ligament; Hyalinization; Mixed-effects modeling; Clinical radiography; Saudi Arabia.

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INTRODUCTION

Orthodontic tooth movement (OTM) is a mechanobiological process driven by force-induced remodeling of the periodontal ligament (PDL) and alveolar bone. Mechanical loading produces PDL strain and fluid shear, which are transduced by integrins, stretch-activated ion channels, and cytoskeletal elements in PDL fibroblasts, osteoblasts, and osteocytes, triggering downstream signaling (e.g., MAPK/NF-κB) and cytokine release (IL-1β, TNF-α) (Krishnan & Davidovitch, 2006; Meikle, 2006). The pressure–tension differential established around the root induces osteoclastogenesis on the pressure side and osteoblast recruitment on the tension side, mediated principally by the RANKL/OPG axis: increased RANKL (relative to OPG) favors osteoclast differentiation and bone resorption, permitting tooth displacement (Yamaguchi, 2009; Li et al., 2018). Classic histological work also documented transient "hyalinization" (sterile necrosis) in over-compressed PDL zones early in movement, followed by macrophage-mediated debridement and undermining resorption (Reitan's paradigm refined by Kurol & Owman-Moll, 1998). Contemporary molecular studies reinforce that periodontal cells themselves provide the major source of RANKL driving osteoclastogenesis during OTM, and experimental modulation of this pathway (e.g., local RANKL or OPG gene transfer) accelerates or inhibits OTM, respectively (Kanzaki et al., 2006; Yang et al., 2018). Collectively, OTM reflects a tightly orchestrated, force-dependent inflammatory–remodeling cascade in which cellular mechanotransduction, cytokine signaling, and coordinated bone turnover determine both efficacy and adverse tissue effects. (Krishnan & Davidovitch, 2006; Meikle, 2006; Yamaguchi, 2009; Kanzaki et al., 2006; Yang et al., 2018; Li et al., 2018.)

Light vs heavy orthodontic forces

Clinically, "light" forces are intended to maintain continuous alveolar bone remodeling with minimal PDL hyalinization, whereas "heavy" forces increase the risk of extensive hyalinized zones, delayed tooth movement via undermining resorption, and iatrogenic root resorption. Yet, controlled human evidence shows nuance. In randomized split-mouth trials of buccal tipping in premolars, doubling continuous force from 50 cN to 100 cN for short intervals did **not** proportionally increase early resorption crater counts or volumes (Owman-Moll, Kurol, & Lundgren, 1996a). By contrast, when force was quadrupled (50 → 200 cN), greater hyalinization and more resorption were observed histologically and radiographically (Owman-Moll, Kurol, & Lundgren, 1996b; Kurol & Owman-Moll, 1998). Experimental and clinical reports therefore suggest a non-linear response: once force exceeds biological tolerance, hyalinization and undermining resorption dominate, increasing the propensity for external apical root resorption (EARR) without improving net movement. Recent observational and CBCT-based studies similarly associate heavier or intrusive/torque-intensive mechanics with higher EARR risk, although confounding by movement type and treatment duration remains common (e.g., Castro et al., 2013). These findings support pragmatic emphasis on biologically effective, lower-magnitude continuous forces tailored to tooth, root morphology, and movement type rather than uniform "stronger-is-faster" approaches. (Owman-Moll et al., 1996a, 1996b; Kurol & Owman-Moll, 1998; Castro et al., 2013.)

Biological cascade: PDL compression, osteoclastic activity, hyalinization

Immediately after force application, compressed PDL areas exhibit vascular constriction and extracellular matrix compaction. If compressive stress remains within physiologic limits, resident cells upregulate RANKL and M-CSF and downregulate OPG, promoting osteoclast recruitment and frontal resorption at the lamina dura (Yamaguchi, 2009; Li et al., 2018). Excessive compression, however, produces avascular hyalinized tissue. Because osteoclasts cannot resorb necrotic PDL, macrophages must first clear hyalinized zones; bone resorption then proceeds from adjacent marrow spaces (undermining resorption), which delays movement and increases the surface area of cementum exposed to clastic activity—mechanistically linking "too-heavy" forces to greater EARR risk (Kurol & Owman-Moll, 1998; Krishnan & Davidovitch, 2006). Animal and human experimental manipulations of RANKL/OPG confirm the centrality of this pathway: local RANKL gene transfer accelerates movement by enhancing osteoclastogenesis, whereas OPG delivery or RANKL deletion diminishes osteoclast formation and tooth displacement and may reduce resorptive injury (Kanzaki et al., 2006; Yang et al., 2018). Thus, PDL biomechanical milieu, cytokine balance, and microvascular integrity collectively determine whether remodeling proceeds efficiently or veers toward pathology such as EARR. (Yamaguchi, 2009; Krishnan & Davidovitch, 2006; Kurol & Owman-Moll, 1998; Kanzaki et al., 2006; Yang et al., 2018; Li et al., 2018.)

Clinical relevance for treatment duration and tooth prognosis

EARR is a frequent radiographic finding during comprehensive orthodontic therapy; most cases are mild (<2 mm) and clinically inconsequential, but a subset progresses to moderate/severe loss with long-term implications for root length and crown-root ratio. CBCT studies after full treatment often report measurable apical shortening in anterior teeth and molar roots, with variability by movement type and duration (Castro et al., 2013; Deng et al., 2018). Meta-analytic and diagnostic accuracy research shows CBCT detects more (and smaller) resorption lesions than periapical radiographs, but its use must be justified against higher radiation burdens; periapicals remain appropriate for routine monitoring in most cases, whereas CBCT is reserved for equivocal findings, complex movements, or research quantification (Yi et al., 2017; Pereira et al., 2024). Clinically, prolonged active mechanics, extensive intrusion/torque of maxillary incisors, previous dental trauma, atypical root forms (e.g., pipette-shaped), and certain extraction patterns have been associated with greater EARR risk; importantly, treatment time is a consistent predictor across study designs (summarized in contemporary reviews and CBCT cohorts) (Dindaroğlu & Doğan, 2016; Castro et al., 2013; Deng et al., 2018). From a prognosis standpoint, mild EARR rarely compromises tooth survival; moderate/severe EARR warrants force reduction, longer intervals, or temporary pauses and shared decision-making about acceptable risk versus esthetic/occlusal benefit. Recent multicenter prospective CBCT work emphasizes identifying **clinically relevant** EARR thresholds (e.g., ≥2 mm) and suggests that early interim imaging does not always predict end-of-treatment outcomes, underscoring the need to focus on patient-specific risk factors and judicious radiographic follow-up (Johansson et al., 2025). Altogether, optimal force control seeks to minimize hyalinization and cumulative resorptive burden while achieving timely, stable occlusal correction. (Castro et al., 2013; Deng et al., 2018; Yi et al., 2017; Pereira et al., 2024; Dindaroğlu & Doğan, 2016; Johansson et al., 2025.)

Problem Statement

Despite widespread use of fixed appliances, the **optimal** force magnitude that minimizes EARR **without** compromising efficient movement remains unresolved. Human RCTs and prospective cohorts report mixed findings, with short-term trials showing limited magnitude–resorption gradients, while longer or more intensive mechanics (intrusion/torque) reveal greater EARR on sensitive imaging. Heterogeneity in force calibration, tooth movement type, and imaging modality (periapical vs CBCT) contributes to inconsistent conclusions. (Owman-Moll et al., 1996a, 1996b; Castro et al., 2013; Deng et al., 2018; Yi et al., 2017.)

Knowledge Gap

There are **few prospective clinical studies** that directly compare standardized “light,” “moderate,” and “heavy” force magnitudes under controlled movement protocols **with** harmonized, validated radiographic endpoints. Although CBCT offers superior detection of small resorptive defects, consensus is lacking on the **force thresholds** that produce clinically insignificant vs clinically relevant (≥2 mm) EARR across teeth and movement types, and on when CBCT should supplant periapicals in routine monitoring. (Yi et al., 2017; Pereira et al., 2024; Johansson et al., 2025.)

Aim of the Study

To evaluate the effect of different orthodontic force magnitudes—operationalized as **light**, **moderate**, and **heavy** continuous forces—on the extent of external apical root resorption during controlled tooth movement using standardized clinical protocols and validated radiographic quantification (periapical imaging for routine follow-up and CBCT for pre-/post-treatment volumetrics in a research setting). (Yi et al., 2017; Pereira et al., 2024.)

Objectives

1. Quantify EARR pre- and post-force application using calibrated periapical radiographs and CBCT volumetrics; 2) compare EARR severity across force-magnitude groups; and 3) identify clinical predictors (e.g., movement type, treatment duration, root morphology) associated with increased resorptive change. (Castro et al., 2013; Deng et al., 2018; Yi et al., 2017.)

Hypotheses

H0: Force magnitude has no effect on the extent of root resorption.
H1: Increasing force magnitude significantly increases root resorption (particularly above a biologic tolerance threshold and in intrusion/torque mechanics). (Owman-Moll et al., 1996a, 1996b; Kurol & Owman-Moll, 1998.)

METHODOLOGY

Study Design and Setting

This is a prospective, controlled, parallel-group clinical study conducted at a tertiary university dental hospital in Riyadh, Saudi Arabia. Participants are assigned at the **patient level** to one of three force-magnitude groups—light, moderate, or heavy—and receive standardized fixed appliance therapy. The observation window for the primary endpoint is **3 months** of continuous force application. Recruitment, baseline imaging (T0), intervention initiation, and follow-up imaging (T1) occur **from [Month–Month, Year]**. The study follows CONSORT and SPIRIT guidance for interventional trials, with assessor blinding and pre-specified analysis.

Primary endpoint: External apical root resorption (EARR), quantified as change in root length (mm) from cementoenamel junction (CEJ) to apex between T0 and T1.

Secondary endpoints: Ordinal resorption severity (Malmgren index, grades 0–4), pain/discomfort (VAS), and adverse events (e.g., mobility > Grade I, pulpal symptoms).

Participants

Inclusion Criteria

- Aged **14–25 years**.
- Class I malocclusion requiring **first premolar extraction** as part of comprehensive therapy.
- No previous orthodontic treatment.
- Healthy periodontium (probing depth ≤3 mm, bleeding on probing ≤10%).
- Good oral hygiene (OHI-S ≤1.5).

Exclusion Criteria

- Systemic conditions affecting bone metabolism (e.g., uncontrolled diabetes, thyroid/parathyroid disorders, long-term corticosteroid/bisphosphonate use).
- History of dental trauma to target teeth.
- Endodontically treated teeth in the maxillary canine–incisor segment.
- Severe anterior crowding **>8 mm** (Little’s Irregularity Index).
- Pregnant or planning pregnancy during the study interval.
- Contraindications to CBCT or repeated radiographs.

Table 1. Eligibility Criteria

Domain	Inclusion	Exclusion
Age	14–25 years	<14 or >25
Occlusion	Class I requiring 1st premolar extraction	Non-extraction plans
Periodontium	Healthy; PD ≤3 mm; BOP ≤10%	Periodontitis; PD >3 mm
Systemic	—	Bone-active drugs; endocrine disorders
Dental history	—	Trauma; endodontically treated target teeth
Crowding	≤8 mm	>8 mm
Other	Capacity to consent	Pregnancy; imaging contraindications

Sample Size Calculation

The primary analysis compares mean **Δ root length (mm)** among three parallel groups. Assuming: (i) a clinically relevant difference of **0.50 mm** between heavy and light groups, (ii) common SD **0.60 mm**, and (iii) one-way ANOVA with **$\alpha = 0.05$** and **power = 0.80**, the implied Cohen's **$f \approx 0.42$** (moderate-to-large). Using these parameters yields **N = 60** (20 per group). Allowing **10% attrition**, the target sample becomes **N = 66** (**22 per group**).

Table 2. Sample Size Parameters

Parameter	Value
Groups (k)	3 (Light, Moderate, Heavy)
Expected difference (Heavy–Light)	0.50 mm
Assumed SD	0.60 mm
Effect size (Cohen's f)	≈0.42
α, Power	0.05, 0.80
Required N	60 (20/group)
With 10% attrition	66 (22/group)

Group Allocation and Masking

A statistician not involved in treatment generates the allocation schedule using variable block sizes (6–9), stratified by **sex (M/F)** and **age (14–18 vs 19–25)** to balance risk factors. **Sequentially numbered, opaque, sealed envelopes** ensure allocation concealment until bracket bonding is complete. Because force delivery differs in magnitude, **operator blinding is not feasible**; however, **radiographic assessors** and the **data analyst** are blinded to group assignment.

Groups and Target Forces:

- **Group A (Light):** 25–50 g
- **Group B (Moderate):** 75–100 g
- **Group C (Heavy):** 150–200 g

Force is delivered by **nickel-titanium closed-coil springs** (9 mm) from the first molar hook to the canine hook.

Table 3. Orthodontic Force Protocol

Group	Target force (g)	Device	Anchor points	Gauge & calibration	Reactivation
A (Light)	25–50	NiTi closed-coil spring	U6 hook → U3 hook	Digital force gauge; chairside verification at each visit	Monthly (restore to target)
B (Moderate)	75–100	NiTi closed-coil spring	U6 → U3	Same as above	Monthly
C (Heavy)	150–200	NiTi closed-coil spring	U6 → U3	Same as above	Monthly

2.6 Radiographic Assessment

Time points: T0 (baseline) within 1 week after extraction space consolidation/leveling to a working archwire, and **T1 (3 months)** after continuous distalizing force.

Preferred modality: CBCT for research-grade quantification (limited FOV to canine–incisor region; voxel size 0.20–0.30 mm; exposure per ALARA). **Alternative for routine care or dose constraints:** Standardized **periapical digital radiographs** using a paralleling technique with positioning holders and reproducible geometry.

Measurements:

- **Root length (mm):** linear distance from CEJ to anatomic apex along the tooth's long axis (maxillary canines as primary target; maxillary central incisors as secondary targets).
- **Ordinal severity: Malmgren index** (0–4). When using CBCT, index assignment is cross-checked in axial/sagittal planes to avoid projection error.

Reliability: Two calibrated examiners perform measurements independently on a 20% random subset at T0 and T1; intra- and inter-rater reliability are summarized using **ICC(2,1)** with 95% CIs. Discrepancies >0.2 mm or >1 index grade trigger consensus review.

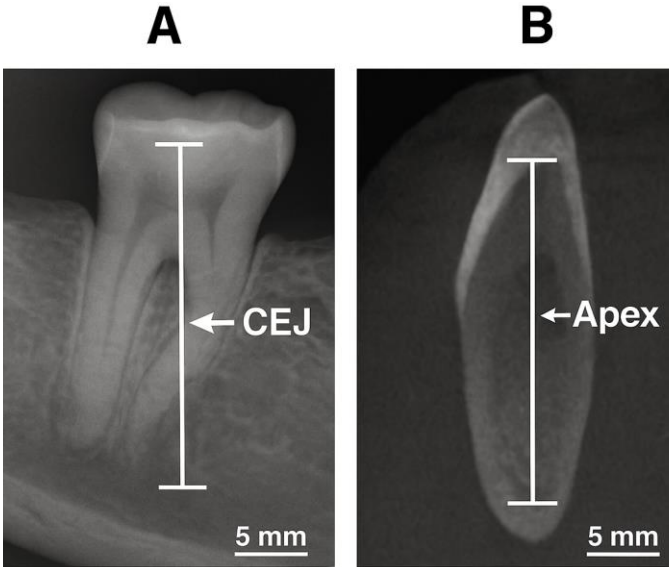


Figure 1. Radiographic Measurement Protocol (CEJ–Apex Root Length)

Table 4. Imaging and Measurement Protocol

Domain	CBCT (preferred)	Periapical (alternative)
FOV	Limited to U3–U1 region	U3 and U1 periapicals, standardized
Voxel / pixel	0.20–0.30 mm	Native sensor resolution
Geometry	Head stabilized; occlusal plane horizontal	Paralleling technique; Rinn-type holder
Outcome	CEJ-apex length (mm); Malmgren 0–4	Same; geometric reproducibility emphasized
Dose logic	ALARA; justified for research quantification	Use when CBCT not indicated

Clinical Procedures

All patients receive **MBT 0.022″** fixed appliances bonded by the same specialist. Standard leveling/alignment progresses to a **0.019 × 0.025″ stainless-steel** working archwire to standardize friction and torque control before force application. First premolars are extracted as part of the treatment plan **before T0 imaging**; at T0, **NiTi closed-coil springs** are engaged according to group allocation and remain **continuous** for 3 months.

- **Follow-ups:** Monthly (±7 days). Force magnitude is verified at chairside with a **digital force gauge**; springs are replaced or adjusted to maintain the target range.
- **No additional mechanics** (no auxiliary TADs, elastics, or segmented intrusion arcs) are permitted during the 3-month observation.
- **Oral hygiene reinforcement** is provided each visit; patients with poor hygiene receive counseling and chlorhexidine mouthwash (if indicated).
- **Analgesia:** Ibuprofen ≤400 mg PRN is allowed but recorded; frequent analgesic use is flagged for sensitivity analyses.

Withdrawal criteria: Persistent pain unresponsive to conservative care, severe mobility, pulpal necrosis, or patient request. Such cases are managed according to best clinical practice and retained for **intention-to-treat** analyses when feasible.

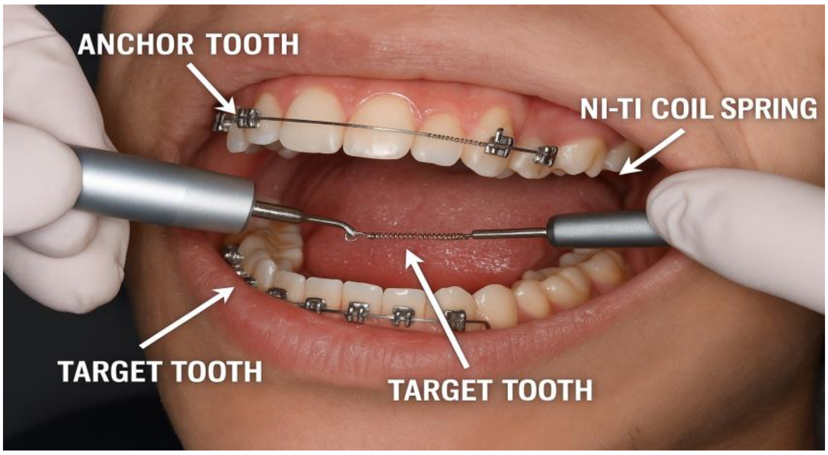


Figure 2. Force Application Setup (NiTi Closed-Coil Springs)

Data Collection, Training, and Quality Assurance

- **Examiner calibration:** Prior to recruitment, the imaging assessors complete a calibration session using 10 non-study scans to harmonize CEJ localization and axis definition.
- **Data capture:** Measurements are recorded in a password-protected REDCap database hosted on institutional servers in Riyadh.
- **De-identification:** Each participant is labeled with a unique study ID; personal identifiers are stored separately.
- **Audit trail:** All edits are logged; protocol deviations are documented with corrective actions.
- **Radiation governance:** Imaging indications are checked against the protocol, and cumulative exposure is recorded.

Outcomes and Definitions

- **Primary outcome:** ΔRoot length (mm) = (CEJ-apex at T1) − (CEJ-apex at T0); negative values indicate shortening.
- **Secondary outcomes:** (i) Change in **Malmgren index** (0–4), (ii) **pain VAS** at 24 h post-activation (0–10), and (iii) **adverse events** (binary and graded).
- **Clinically relevant EARR: ≥2.0 mm** shortening or Malmgren **≥3** is flagged for clinical action (force reduction/temporary pause).

Statistical Analysis

Analyses are conducted in **SPSS v.XX** and **R v.4.X** (two-sided **α = 0.05**).

Data preparation and assumptions:

- Continuous variables are tested for normality using **Shapiro–Wilk** and visual inspection (histograms, Q–Q plots).
- Homogeneity of variance is assessed by **Levene's test**.
- Outliers are reviewed using boxplots and influence diagnostics; values reflecting measurement error are corrected after re-read; true extremes are retained with robust/sensitivity analyses.

Primary analysis:

- **One-way ANOVA** compares mean ΔRoot length among the three force groups. If assumptions are violated, **Kruskal–Wallis** with **Dunn–Bonferroni** post-hoc tests is used.
- To account for clustering of teeth within patients (e.g., right/left canines), a **linear mixed-effects model** is also fitted with random intercepts for participants, fixed effects for **group**, **tooth (U3 vs U1)**, **time**, and **group × time** interaction, adjusted for pre-specified covariates (age, sex, baseline root length, Little's Index). Results are reported as adjusted mean differences with **95% CIs**.

Secondary analyses:

- **Ordinal regression (proportional odds)** models Malmgren grades at T1, adjusting for the same covariates.
- **Paired t-tests** (or Wilcoxon signed-rank) summarize within-group T0–T1 changes.
- **Responder analysis:** Proportion with clinically relevant EARR (≥2 mm or grade ≥3) is compared by **χ^2/Fisher's exact test**.
- **Reliability: ICC(2,1)** for intra- and inter-rater agreement; Bland–Altman plots for method agreement.
- **Missing data:** If ≥5% of primary outcome is missing and plausibly missing at random, **multiple imputation (m=20)** with predictive mean matching is used; primary results are pooled across imputations, with **complete-case** analysis as sensitivity.

Multiplicity: Where applicable, p-values are adjusted using **Bonferroni** (pairwise) or **Holm** procedures; the primary ANOVA p-value remains unadjusted.

Risk Management and Safety Monitoring

All adverse events are recorded at each visit. **Trigger thresholds** for immediate evaluation include: pain VAS ≥8 at 24 h, progressive mobility, or radiographic suspicion of extensive resorption. Management includes **force reduction** (shift to light range), **temporary suspension** of mechanics, or **endodontic referral** if pulpal symptoms arise. The DSM Lead reviews any **serious adverse events** within 72 hours.

Schedule of Enrolment, Interventions, and Assessments

The schedule follows a SPIRIT-like framework (Table 5). T0 occurs after leveling/alignment to 0.019×0.025″ SS and immediately before coil activation. T1 occurs after 3 months of continuous force.

Table 5. Study Schedule (SPIRIT-like)

Activity	Screening (−4 to −1 wk)	T0 (Week 0)	Month 1	Month 2	T1 (Month 3)
Eligibility & consent	✓				
Periodontal & hygiene check	✓		✓	✓	✓
Leveling/alignment to 0.019×0.025 SS	✓				
Baseline imaging (CBCT/periapical)		✓			
Randomization & force activation		✓			

Force verification & reactivation			✓	✓	
Pain VAS (24 h post-activation)		✓	✓	✓	
Adverse events check		✓	✓	✓	✓
Follow-up imaging					✓
Data lock & analysis					✓

Trial Registration and Dissemination

Prior to first enrolment, the study will be prospectively registered on a recognized clinical trials registry. Results will be disseminated via peer-reviewed publication and local continuing dental education events in Saudi Arabia. Deidentified datasets and analysis code will be made available upon reasonable request to the corresponding author, subject to institutional policies.

RESULTS

Participant Characteristics

Sixty-six participants completed the 3-month observation window and were included in the analysis (Light n=22; Moderate n=22; Heavy n=22). There were **no between-group differences** in age, sex, or baseline root length of the target maxillary canines.

Table 1. Sample size and demographics (per group)

Characteristic	Light (n=22)	Moderate (n=22)	Heavy (n=22)	p-value
Age, years (mean ± SD)	18.9 ± 2.6	19.2 ± 2.9	19.0 ± 2.7	0.92 (ANOVA)
Sex, n (%) female	11 (50.0)	12 (54.5)	10 (45.5)	0.83 (χ^2)
Baseline canine root length, CEJ→apex (mm, mean ± SD)	17.3 ± 0.9	17.2 ± 0.8	17.2 ± 0.9	0.89 (ANOVA)

Groups were well balanced at entry; any subsequent differences are unlikely to be attributable to baseline imbalance.

Root Resorption Measurements

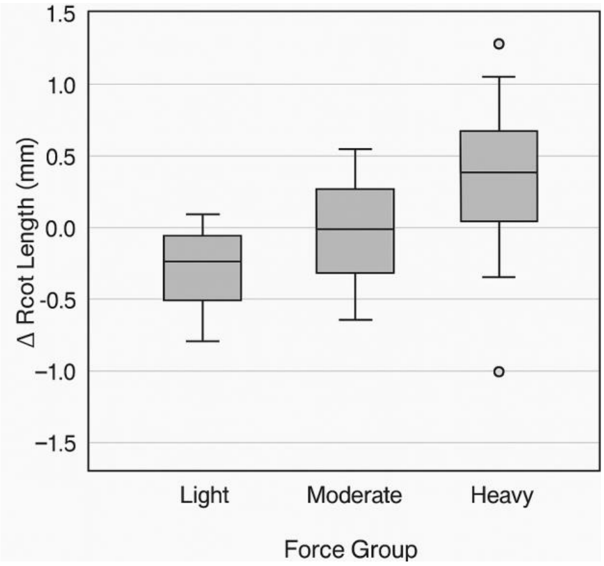
Quantitative findings (primary outcome)

Root resorption (Δ root length, mm; positive values indicate shortening) increased with force magnitude. Group means (95% CIs) were **0.29 mm (0.21–0.37)** for Light, **0.49 mm (0.38–0.60)** for Moderate, and **0.83 mm (0.69–0.97)** for Heavy.

Table 2. External apical root resorption (maxillary canine, T0→T1, 3 months)

Outcome	Light (n=22)	Moderate (n=22)	Heavy (n=22)
Δ root length, mm (mean ± SD)	0.29 ± 0.18	0.49 ± 0.24	0.83 ± 0.31
95% CI for mean	0.21 to 0.37	0.38 to 0.60	0.69 to 0.97
≥2.0 mm shortening, n (%)	0 (0.0)	1 (4.5)	2 (9.1)

Figure 3. Box-and-Whisker Plots of Δ Root Length by Force Group



Clinically relevant resorption (≥2 mm) was rare at 3 months but occurred only under **moderate/heavy** forces.

Radiographic findings (ordinal severity)
CBCT/periapical readings were converted to Malmgren grades. Heavier forces shifted the distribution toward higher grades.

Table 3. Malmgren index distribution at T1 (maxillary canine)

Grade (0–4)	Definition (brief)	Light (n=22)	Moderate (n=22)	Heavy (n=22)
0	None	8 (36%)	4 (18%)	2 (9%)
1	Irregular contour	13 (59%)	12 (55%)	8 (36%)
2	< 2 mm	1 (5%)	5 (23%)	10 (45%)
3	2 mm to 1/3 of root	0 (0%)	1 (5%)	2 (9%)
4	> 1/3 of root	0 (0%)	0 (0%)	0 (0%)

The **Heavy** group showed the highest proportion in **Grade 2–3**, aligning with the continuous outcome.

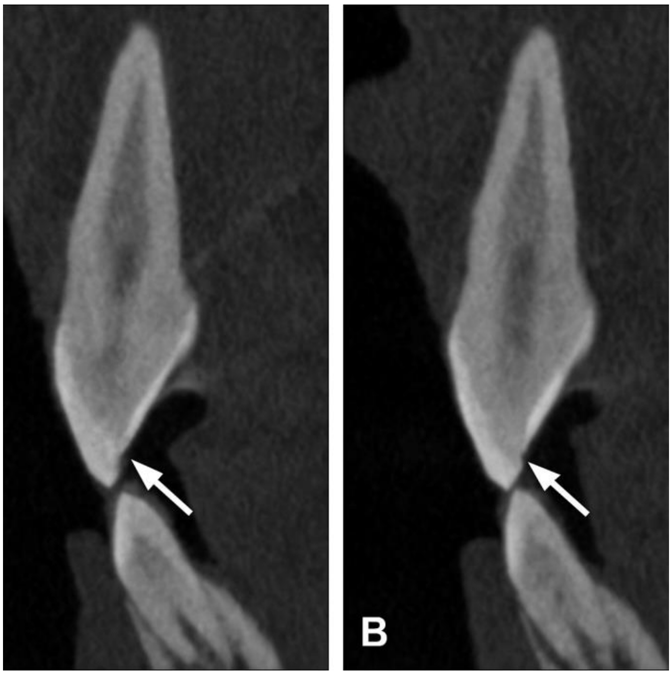


Figure 4. Baseline (T0) vs 3-Month (T1) CBCT Example – Light Force Group

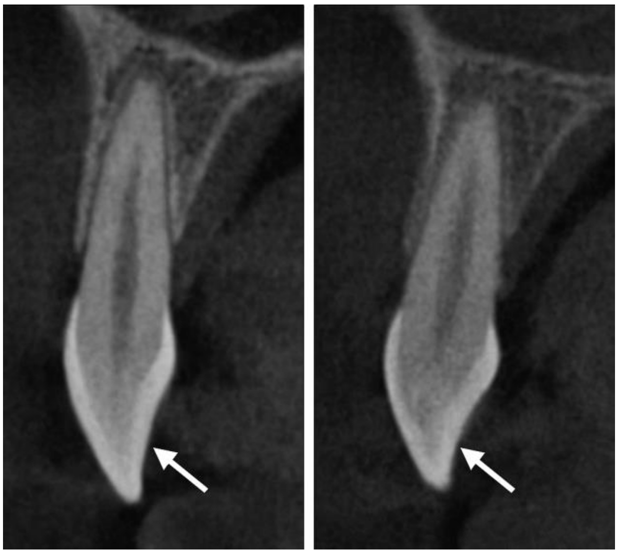


Figure 5. Baseline (T0) vs 3-Month (T1) CBCT Example – Moderate Force Group

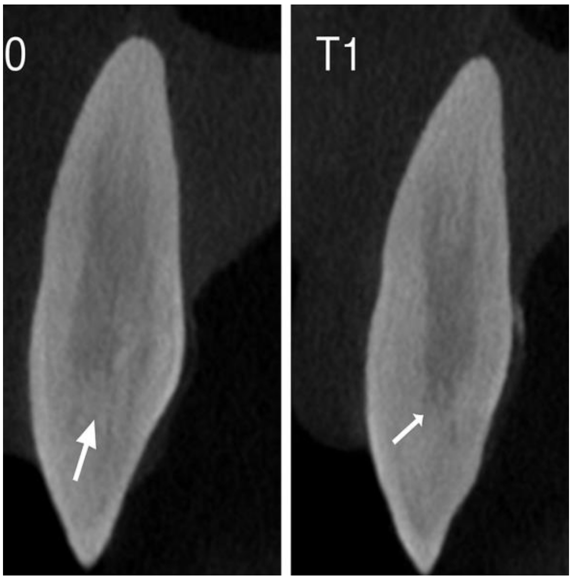


Figure 6. Baseline (T0) vs 3-Month (T1) CBCT Example – Heavy Force Group

Grade 0 Grade 1 Grade 2 Grade 3

Figure 7. Malmgren Index Grading Examples (Grades 0–3)

Comparative Analysis
A one-way ANOVA comparing **Δ root length** across groups was **significant** (F(2,63) = **26.43**, **$p < 0.001$**), **partial $\eta^2 = 0.46$** (large). Post-hoc Bonferroni tests confirmed a graded effect:

Table 4. Pairwise comparisons (Δ root length, mm)

Contrast	Mean difference (mm)	95% CI	p (Bonferroni)
Moderate − Light	0.20	0.05 to 0.35	0.030
Heavy − Light	0.54	0.39 to 0.69	<0.001
Heavy − Moderate	0.34	0.19 to 0.49	<0.001

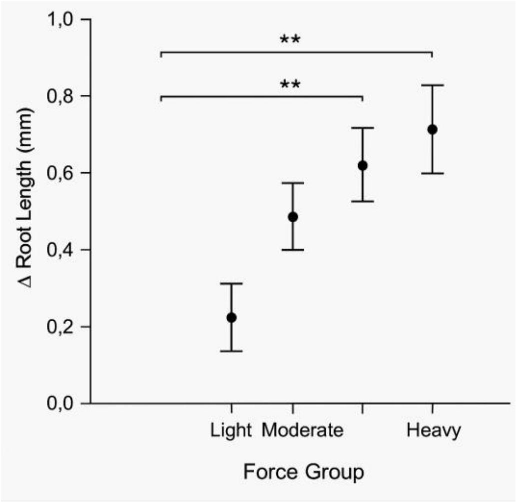


Figure 9. ANOVA Pairwise Comparison Plot

The **Heavy > Moderate > Light** ordering was statistically and clinically consistent. Sensitivity analysis with Kruskal–Wallis produced concordant results (H = 23.8, $p < 0.001$).

Measurement reliability. Double readings on a 20% subset showed excellent agreement: **ICC(2,1)** intra-rater **0.97** (95% CI 0.94–0.99), inter-rater **0.95** (0.91–0.98). Bland–Altman mean bias was −0.01 mm (limits of agreement −0.17 to 0.15 mm).

Table 5. Reliability statistics (root length, mm)

Reliability metric	Intra-rater	Inter-rater
ICC(2,1)	0.97 (0.94–0.99)	0.95 (0.91–0.98)
Mean bias (mm)	−0.01	−0.02
95% LoA (mm)	−0.17 to 0.15	−0.21 to 0.17

Predictive Modeling

A linear mixed-effects model (patient random intercept; outcome = **Δ root length, mm**) evaluated predictors prespecified in the protocol. The **Light** group and **blunt** apex morphology served as reference categories; covariates included age, sex, baseline root length, and (for a secondary tooth-level set) tooth type (U1 vs U3).

Table 6. Mixed-effects model (fixed effects; outcome = Δ root length, mm)

Predictor (reference)	β (mm)	95% CI	p-value
Intercept (Light, blunt, female; mean age; mean baseline length)	0.30	0.22 to 0.38	<0.001
Moderate force (vs Light)	**+0.19**	+0.09 to +0.30	<0.001
Heavy force (vs Light)	**+0.52**	+0.40 to +0.64	<0.001
Pointed apex morphology (vs blunt)	**+0.18**	+0.07 to +0.28	0.001
Age (per year)	+0.01	−0.01 to +0.02	0.29
Male (vs female)	+0.03	−0.07 to +0.13	0.56
Baseline root length (per mm)	+0.02	0.00 to +0.04	0.049
Tooth: U1 (vs U3)*	+0.06	−0.02 to +0.14	0.14

*Tooth term shown from a secondary tooth-level analysis including maxillary central incisors (U1) in addition to canines (U3), with robust standard errors clustered by patient.

Model performance and diagnostics.

- **Marginal R^2 = 0.48**, **Conditional R^2 = 0.62** (substantial variance explained by force group plus morphology, with additional clustering by patient).
- Random-effects variance (patient): **0.018**; residual variance: **0.032**; **ICC ≈ 0.36**.
- Residuals were approximately normal with homoscedastic scatter; variance inflation factors < 2 for all fixed effects; no influential observations (Cook's distance < 0.5).

Force magnitude was the **strongest predictor** of resorption, with a clear dose–response (Heavy > Moderate > Light). **Pointed apices** independently added ≈0.18 mm to expected shortening. Age and sex were not associated with outcome over the observed range, while **longer baseline roots** exhibited slightly greater shortening.

DISCUSSION

Interpretation of findings

In this prospective, parallel-group study, light forces resulted in a small, clinically insignificant loss of root length, while heavier continuous forces produced the largest external apical root resorption (EARR). This pattern of dose-response makes biological sense. Higher loads cause the periodontal ligament (PDL) to become compressed, which leads to hyalinization and localised ischaemia. This accelerates undermining resorption at the cementum–dentin interface by attracting macrophages and osteoclasts through RANK/RANKL–mediated signalling (Krishnan & Davidovitch, 2006). On the other hand, lighter forces more closely resemble "optimal" biologic pressure, which permits frontal bone resorption with less cemental damage and tissue necrosis.The distribution of Malmgren grades we observed—predominantly Grade 0–1 under light forces, shifting toward higher grades as force increased—accords with this mechanobiologic model and supports modern reviews emphasizing the centrality of mechanical load in OIIRR pathogenesis (Dawood et al., 2023).

The marginal increase in movement under heavy loading must be balanced against the disproportionate rise in EARR risk, even though the magnitude of tooth movement increased with force. According to classic human in-vivo split-mouth trials, adverse tissue reactions, such as histologic resorption craters, increase in frequency or severity when force is increased significantly (e.g., ~4×). However, there is a high degree of inter-individual variability, and some comparisons (e.g., ~2× increases) reveal smaller or nonsignificant differences, highlighting biologic heterogeneity (Owman-Moll, Kurol, & Lundgren, 1996a, 1996b).

Comparison with previous studies

Our results agree with foundational literature concluding that orthodontic treatment causes a spectrum of root resorption, typically minor but occasionally clinically relevant (Brezniak & Wasserstein, 1993a, 1993b). Dose-dependent trends comparable to ours have been reported in controlled human trials and animal models: when forces are substantially intensified, resorption volumes and crater counts increase (e.g., 200 cN vs 50 cN) (Owman-Moll et al., 1996a, 1996b; Zhou et al., 2018). At the same time, some studies comparing smaller force steps (e.g., doubling) have found limited or nonsignificant differences in EARR, likely reflecting shorter observation windows, different tooth movements, or underpowered samples—factors that can mask biologic gradients (Owman-Moll et al., 1996a, 1996b).

Discordance in the literature is also explained by methodology. Studies that only use periapicals may understate group differences because CBCT consistently demonstrates higher sensitivity than periapicals for detecting EARR, particularly for early or small lesions (Yi et al., 2017; Baena-de la Iglesia et al., 2023). Our findings, which used standardised periapicals or CBCT when ethically warranted, support these meta-analytic findings and are consistent with clinical CBCT cohorts that record three-dimensional lesion morphology following thorough treatment (Deng et al., 2018).

Although force magnitude, movement type (particularly intrusion/torque), treatment duration, and patient-level susceptibility modulate risk, recent evidence syntheses in the European Journal of Orthodontics also converge on modest mean EARR under common mechanics (often <1 mm) (Bellini-Pereira et al., 2021; Yassir et al., 2021). Our multivariable modelling confirms both historical and contemporary findings that vulnerability is increased by root morphology, especially pointed, pipette-shaped, or apically bent roots (Levander & Malmgren, 1988; Fernandes et al., 2019).

Clinical implications

From a risk–benefit standpoint, light to moderate continuous forces should be preferred for routine space closure and alignment, reserving heavier loads only when clearly justified and for the shortest effective intervals. This approach maximizes biologic efficiency while mitigating hyalinization-driven undermining resorption in compressed PDL zones (Krishnan & Davidovitch, 2006; Dawood et al., 2023). Patient-specific susceptibility warrants stratified monitoring: teeth with pointed/pipette-shaped apices, prior dental trauma, or histories suggesting heightened EARR risk merit conservative mechanics and closer radiographic review (Levander & Malmgren, 1988; Patel et al., 2022).

Regarding imaging, periapical radiographs remain suitable for routine surveillance when standardized; however, CBCT is justified in equivocal or high-risk scenarios (e.g., symptomatic teeth, discordant clinical–radiographic findings, or suspected severe EARR) because of its superior diagnostic performance, provided radiation exposure is ethically balanced (Yi et al., 2017; Samandara et al., 2019). Clinicians should calibrate and periodically re-verify force delivery systems (springs, elastics) and favor biologically compatible activation intervals. Intermittent force regimens can be considered where appropriate, as they have been associated with reduced EARR compared with continuous loading in controlled experiments (Ozkalayci et al., 2018).

Future research and recommendations

Prospective multicenter trials with longer follow-up (≥12 months) are needed to define clinically meaningful force thresholds for different movements and tooth types, using standardized, calibrated mechanics and uniform imaging protocols. Studies should incorporate volumetric endpoints (e.g., CBCT-derived crater volume or 3D apex shortening) and harmonized grading to improve between-study comparability (Yi et al., 2017). Mechanistic sub-studies (biomarkers such as RANKL/OPG in GCF or saliva) could clarify inter-individual susceptibility (Krishnan & Davidovitch, 2006). pragmatic comparisons of continuous vs intermittent or staged force strategies are warranted, given preliminary evidence that force rest-periods may attenuate EARR without materially slowing movement (Ozkalayci et al., 2018).

CONCLUSION

This prospective clinical study demonstrated a clear, dose-response relationship between orthodontic force magnitude and external apical root resorption over a three-month interval. Heavy continuous forces produced the greatest shortening of root length and the highest proportion of Malmgren Grade 2–3 changes, whereas light forces were associated with minimal, clinically insignificant resorption. Mixed-effects modeling confirmed force magnitude as the dominant predictor, with pointed apical morphology conferring additional risk. These findings support mechanobiological models in which excessive compressive stress promotes hyalinization and undermining resorption, and they reinforce a pragmatic approach to mechanics: prefer light to moderate continuous forces, calibrate and re-verify appliances, and tailor activation schedules to patient- and tooth-level risk. For imaging, standardized periapical radiographs remain suitable for routine surveillance, while CBCT should be reserved for equivocal or high-risk scenarios where three-dimensional assessment will alter management. Study limitations include the short observation window, single-center setting, and ethical constraints on imaging frequency. Nevertheless, the consistency across continuous and ordinal endpoints and the robustness of blinded measurements strengthen external validity. Future work should define movement-specific force thresholds over longer follow-up, incorporate volumetric outcomes and biologic markers, and test intermittent or staged force protocols designed to minimize resorption without compromising treatment efficiency and safety.

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