Archive of
Orofacial Data Science

AODS Vol. 3 | 2026 | DOI: 10.17879/aods-2026-10242

Meta-Regression Analysis

Effect of Tipping-related Movement on Heterogeneity in Micro-osteoperforation-assisted Canine Retraction

Pei Jung Chung[1], Susanne Bierbaum[2,3]

[1]Independent Researcher, Cupertino, CA, USA; [2]International Medical College, University of Technology, Dresden, Germany; [3]Max Bergmann Center of Biomaterials, University of Technology, Dresden, Germany

DOI: 10.17879/aods-2026-10242 | **Received:** June 26, 2026 | **Accepted:** August 24, 2026

Effect of Tipping-related Movement on Heterogeneity in Micro-osteoperforation-assisted Canine Retraction

Pei Jung Chung[1], Susanne Bierbaum[2,3]

[1]Independent Researcher, Cupertino, CA, USA; [2]International Medical College, University of Technology, Dresden, Germany; [3]Max Bergmann Center of Biomaterials, University of Technology, Dresden, Germany

For correspondence: | E-mail: tinachungpj2011@gmail.com

Open Access   Publisher: University of Münster, Germany   Received: June 26, 2026   Accepted: August 24, 2026

ABSTRACT

AIM: The objective of this study was to explore whether force-related and measurement-related factors could explain between-study heterogeneity in the first-month effects of micro-osteoperforation-assisted canine retraction.

METHODS: First-month canine retraction outcomes were extracted for micro-osteoperforation and control groups from randomized clinical trials evaluating micro-osteoperforation-assisted conventional canine retraction. Meta-regression was performed to examine the contribution of two moderators toward between-study heterogeneity: the proximity of the applied force to the canine center of resistance and the measurement-related factors of first-month canine retraction rates.

RESULTS: Nine randomized clinical trials were included in the meta-regression. Adjustment of force-related and measurement-related moderators explained most to all between-study heterogeneity in first-month canine retraction rates (acceleration model R^2=100%; MOP-only model R^2=100%; control-only model R^2=91.47%). Residual heterogeneity was reduced to 0% in the acceleration and MOP-only models and to 44.33% in the control-only model.

CONCLUSION: Biomechanical and measurement-related factors may partially explain the variability across first-month canine retraction rates in micro-osteoperforation-assisted studies. Force proximity to the center of resistance and reference tooth selection should be considered when designing, interpreting, and comparing clinical trials on micro-osteoperforation-assisted canine retraction.

Keywords: Micro-osteoperforation; Canine retraction; Meta-regression; Heterogeneity; Measurement methodology

1. Introduction

Micro-osteoperforation has been proposed as a minimally invasive bone-puncturing procedure to accelerate orthodontic tooth movement. This acceleration is facilitated by a physiological process known as the regional acceleratory phenomenon (RAP), which results from increased bone plasticity and reduced bone density induced by local bone remodelling (Wilcko et al., 2001). Since its introduction in 2010, multiple clinical trials have implemented micro-osteoperforation and reported short-term acceleration of orthodontic tooth movement (Teixeira et al., 2010). However, high heterogeneity and low certainty in systematic reviews have limited the evidence supporting the efficacy of this procedure in accelerating orthodontic tooth movement. Assessment of individual heterogeneous design elements may help to improve the robustness of future reviews and support the development of standardised protocols for future clinical trials.

The proximity of orthodontic force application to the center of resistance of the tooth influences the degree of bodily movement. Variation in the proximity of force application to canine center of resistance may therefore contribute to between-study heterogeneity in maxillary canine retraction rates in studies evaluating micro-osteoperforation-assisted canine retraction. Ribeiro et al. (2016) illustrated different resultant moments generated by different force designs. Force application away from the centre of resistance, in the absence of a counter-moment, generates uncontrolled tipping. Compared with bodily movement, tipping occurs earlier and at a faster rate. Therefore, this study focuses on the potential confounding contribution of orthodontic force design to tooth movement acceleration attributed to micro-osteoperforation.

After micro-osteoperforation, measurements of canine movement at each time interval are used to quantify the magnitude of canine retraction. Two major categories of measurements have been implemented, tooth displacement measurements and tooth-to-tooth distance change measurements using a reference tooth, such as the lateral incisor, second premolar, or first molar. Regardless of anchorage method, tipping of lateral incisors, premolars, and molars may occur during orthodontic treatment. Tooth-to-tooth distance change measurements may incorporate tipping-related positional changes of the reference teeth into the measured canine movement distance, thereby potentially confounding the assessment of canine acceleration attributed to micro-osteoperforation. This study focuses on the contribution to between-study heterogeneity arising from the use of tooth-to-tooth distance change measurements versus tooth displacement measurements.

Orthodontic tooth movement occurs in a multiphasic pattern, with the highest rate during the initial phase before substantial bone remodelling constraints and force decay occur. This initial phase reflects movement within the periodontal ligament and the immediate biomechanical response to applied force. In contrast, later phases are increasingly influenced by bone remodelling, force decay, and anchorage adaptations. By focusing on the first-month canine movement rate, the present study captures a period that is most sensitive to biomechanical factors while minimising the influence of long-term biological variability.

This study aims to investigate the impact of the proximity of orthodontic force application to the canine centre of resistance and the use of tooth-to-tooth distance change measurements on heterogeneity among clinical trials evaluating maxillary canine retraction accelerated by micro-osteoperforation during conventional orthodontic space-closure treatment. To our knowledge, no previous study has examined how biomechanical force design and measurement methods contribute to between-study heterogeneity in clinical trials of micro-osteoperforation-assisted maxillary canine retraction. Revealing these sources of heterogeneity may help to establish standardised protocols for future clinical trials and thereby support more robust future systematic reviews.

DOI: 10.17879/aods-2026-10242

2. Methods

PubMed, Scopus, and the Cochrane Library were searched with no language restriction using the keywords listed in **Table 1**. For ClinicalTrials.gov entries identified through the Cochrane Library, corresponding publications and related articles were screened. Citation tracing was performed using the reference lists of five studies, Alikhani et al. (2013), Alkebsi et al. (2018), Gasparro et al. (2022), Hashem et al. (2024), and Sivarajan et al. (2019).

Table 1. Electronic database search strategy and citation-tracing sources.

DATABASE	SEARCH KEYWORDS
PubMed	((micro-osteoperforation*) OR (flapless corticotomy)) AND ((canine retraction) OR (space closure))
Scopus	((micro-osteoperforation* OR perforation* OR "flapless corticotomy") AND ("canine retraction" OR "space closure"])
Cochrane Library	((micro-osteoperforation) OR (flapless corticotomy)) AND ((canine retraction) OR (space closure))
Hashem 2024	Citation Tracing
Gasparro 2022	Citation Tracing
Sivarajan 2019	Citation Tracing
Alkebsi 2018	Citation Tracing
Alikhani 2013	Citation Tracing

The inclusion criteria were defined according to the PICOS framework. Randomised split-mouth or parallel-group clinical trials were included if participants received conventional orthodontic treatment for maxillary canine retraction at least three months after maxillary first premolar extraction and were not undergoing treatment in preparation for orthognathic surgery. The intervention consisted of single MOPs or repeated MOPs, provided that no repeated procedure was performed before the first-month canine retraction measurement. MOPs were defined as flapless, mechanically induced, discrete, point-based cortical perforations limited to the buccal side within the region from the mesial aspect of the maxillary canine to the distal aspect of the maxillary second premolar. The control group received no intervention. Canine retraction was initiated immediately after the MOP procedure. The outcome was the first-month canine retraction rate, reported either as an interval rate from the beginning of canine retraction (T0) to one month after canine retraction (T1), or as the cumulative first-month canine retraction rate.

Non-randomised studies, animal studies, and in vitro studies were excluded. Studies involving patients treated with clear aligners or conventional orthodontics in preparation for orthognathic surgery were excluded. Studies involving the following interventions were also excluded, procedures other than MOPs, laser-induced MOPs, repeated MOPs before the first-month canine retraction measurement, MOPs performed on both the buccal and palatal sides, MOPs performed outside the region between the mesial aspect of the maxillary canine and the distal aspect of the maxillary second premolar, or MOPs combined with other interventions. Studies were excluded if extractions were completed within three months before MOP application. Studies in which the control groups received additional interventions were also excluded. Studies were further excluded if canine retraction was initiated after a delay following MOP application. Studies involving en masse anterior retraction or whole anterior segment retraction were excluded. Outcomes reported as canine displacement

DOI: 10.17879/aods-2026-10242

or canine-to-tooth distance changes over intervals shorter than one month, such as 0–2 weeks or 2–4 weeks, absolute canine positions from reference points rather than interval changes, or monthly intervals without standard deviations were also excluded.

Titles and abstracts were initially screened. Studies were excluded at this stage if they were not relevant to the topic, defined as MOP-assisted maxillary canine retraction in conventional orthodontic treatment not performed in preparation for orthognathic surgery. Randomised split-mouth studies, randomised parallel-group studies, and studies with no specification of randomisation were retained for further assessment. At the abstract screening stage, studies reporting control groups with additional interventions were excluded. Studies in which the control group was not specified were retained for full-text screening. Full-text screening was then performed, and studies meeting the inclusion criteria were included in the final analysis.

462 records were identified in the initial search, with the last search conducted on 26 March 2026. Ten studies fulfilled the inclusion criteria following screening and eligibility assessment. To avoid duplication of overlapping data, El Awady et al. (2019a) was excluded from the quantitative synthesis because the first-month canine retraction rate was reported identically to that in El Awady et al. (2019b). In Ozkan et al. (2021), the control group data were shared across two MOP groups, only the MOP group with 4-mm perforation depth was included in the meta-regression analysis. Overall, nine studies were included in the meta-regression analysis (**Figure 1**).

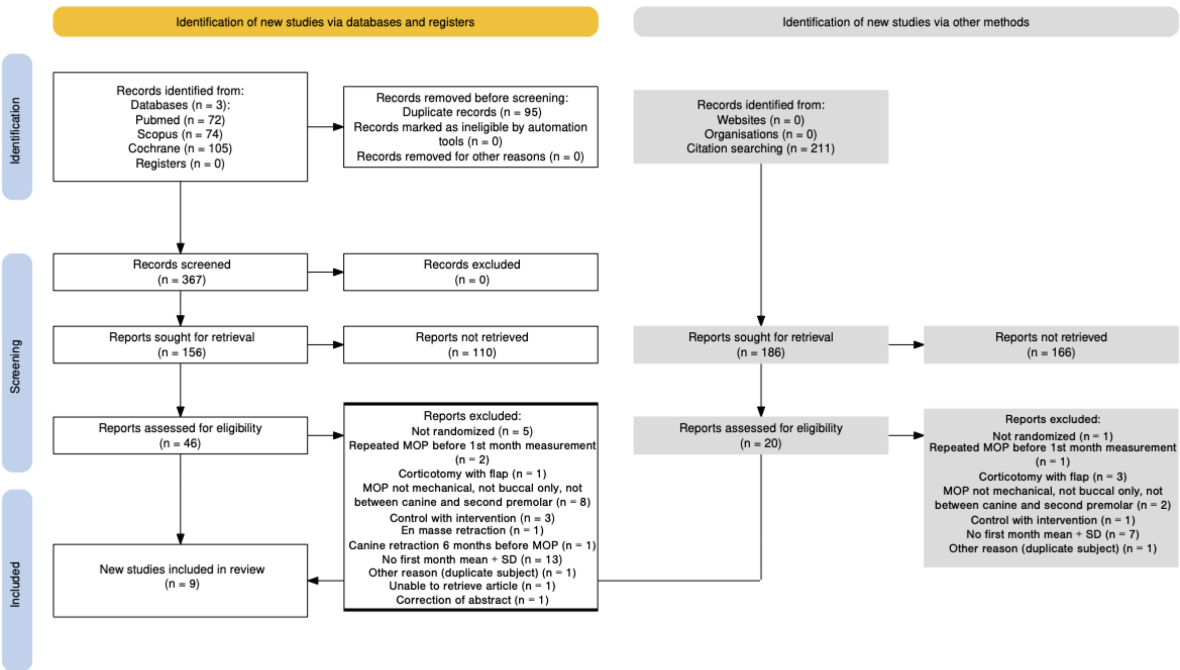

Figure 1. PRISMA flow chart of article selection.

First-month canine movement rates were extracted separately for the MOP and control groups. Biomechanical and measurement-related variables were coded and incorporated into the meta-regression analysis.

Force application relative to the centre of resistance (CR) of the canine was coded according to the location at which the retraction force was exerted on the canine. The variable was categorised as 1 when the force was applied to the canine at a point approximating the canine CR, such as through a canine-attached power arm or an equivalent canine-side extension. It was categorised as

DOI: 10.17879/aods-2026-10242

0 when the force was applied at the bracket or hook level, or when the appliance design only altered the direction or line of action of the force without changing the point of force application on the canine to a CR-level position. For example, force angulation from a molar power arm, temporary anchorage device, anchorage-side auxiliary, or use of a rectangular archwire to promote bodily movement was not coded as force application close to the canine CR unless the force was directly applied to a canine-side attachment positioned near the estimated CR.

Measurement methods were classified into four categories reflecting increasing susceptibility to measurement bias: 0, canine displacement; 1, posterior tooth reference with direct TAD-supported canine retraction; 2, posterior tooth reference without direct TAD-supported canine retraction; and 3, lateral incisor reference. Stable-reference measurements included model or CBCT superimposition, palatal/raphe-based reference lines, or custom palatal reference devices that were not expected to tip or drift during canine retraction.

2.1. Statistics

Meta-regression analyses were performed in R version 4.5.2 using the packages `readxl`, `dplyr`, and `metafor`. Study-level data were imported from an Excel file and processed prior to analysis. The variables `force_CR` and `measurement_bias` were entered as categorical moderators in meta-regression models.

Three analytic perspectives were examined. The separation of perspectives was considered necessary because identical mean differences may arise from different combinations of MOP and control movement rates. For each analytic perspective, an intercept-only random-effects model was calculated first, followed by the respective meta-regression model. Models were fitted using restricted maximum likelihood (REML) estimation. The overall contribution of `measurement_bias` was evaluated using an omnibus test of the corresponding regression coefficients.

In the MOP-only model, the study-specific effect size was defined as the reported mean first-month canine retraction rate (`rate_m1_mop`), with the corresponding sampling variance calculated as SD^2/n using `sd_m1_mop` and `n_m1_mop`. A mixed-effects meta-regression model including `force_CR` and `measurement_bias` as moderators was then fitted.

In the acceleration model, study-specific effect sizes were calculated as the mean difference (MDs) between the MOP and control group based on reported mean, standard deviation, and sample size. These effect sizes were subsequently analyzed in a mixed-effects meta-regression model including `force_CR` and `measurement_bias`.

In the control-only model, the study-specific effect size was defined as the reported mean first-month canine retraction rate (`rate_m1_control`), and the sampling variance was calculated as SD^2/n using `sd_m1_control` and `n_m1_control`. A corresponding mixed-effects meta-regression model with `force_CR` and `measurement_bias` as moderators was fitted.

3. Results

3.1. Risk of bias

Three studies were judged as low risk of bias, whereas six studies were judged as having some concerns. No study was judged as high risk of bias. Most concerns were related to the absence of preregistered protocols or prespecified analysis plans in the domain assessing selection of the reported result (**Figure 2**).

Study ID	Experimental	Comparator	Outcome	Weight	D1	D2	D3	D4	D5	Overall
Alkebsi 2018	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	+	+
El-Awady 2019b	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	!	!
Feizbakhsh 2018	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	!	!
Li 2022	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	!	!
Mangal 2025	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	!	!
Ozkan 2021	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	!	!
Raghav 2022	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	+	+
Thomas 2021	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	+	+
Venkatachalapathy 2022	Micro-osteoperforation	No intervention	First-month maxillary canine retraction rate	1	+	+	+	+	!	!

+ Low risk
! Some concerns
- High risk

D1 Randomisation process
D2 Deviations from the intended interventions
D3 Missing outcome data
D4 Measurement of the outcome
D5 Selection of the reported result

Figure 2. Risk-of-bias assessment for the included studies evaluating the effect of micro-osteoperforation compared with no intervention on the first-month maxillary canine retraction rate. Judgements are presented for each study across the five RoB 2 domains, D1, randomisation process, D2, deviations from the intended interventions, D3, missing outcome data, D4, measurement of the outcome, and D5, selection of the reported result, together with the overall risk-of-bias judgement. Most studies were judged to be at low risk or to raise some concerns overall, with concerns arising predominantly in Domain 5.

3.2. Effects of biomechanical and measurement-related moderators on between-study heterogeneity in first-month maxillary canine retraction rates

In Raghav et al. (2022), although the use of a power arm was described in the Methods section, no power arm was evident in the available clinical images. Therefore, force application was coded as not approximating the centre of resistance (force_CR = 0). In Ozkan et al. (2021), the control group consisted of 24 canines shared across two MOP groups, with 12 canines corresponding to each MOP comparison. To maintain independence of observations, the control data were adjusted to match the number of canines in the selected MOP group with 4-mm perforation depth.

In the acceleration model, defined as the mean difference in first-month canine retraction rate between the MOP and control groups, the pooled acceleration rate was 0.3396 mm/month (95% CI, 0.1977 to 0.4816, $p < 0.0001$). Substantial heterogeneity was observed before moderator adjustment ($\tau^2 = 0.0334$, $I^2 = 78.48\%$, $Q = 39.1362$, $p < 0.0001$).

After adjustment for force application relative to the centre of resistance and measurement method, residual heterogeneity was reduced to $\tau^2 = 0$ and $I^2 = 0.00\%$. The moderators accounted for 100.00% of between-study heterogeneity. The overall test of moderators was significant ($QM = 24.0516$, $p < 0.0001$). Residual heterogeneity was no longer statistically significant ($QE = 1.3457$, $p = 0.5103$).

Compared with the reference measurement category, lateral incisor reference measurement was associated with a higher observed acceleration effect (estimate = 0.3021, 95% CI, 0.1243 to 0.4799, $p = 0.0009$). Other measurement categories were not statistically significant.

In the MOP-only model, the pooled first-month canine retraction rate was 1.1590 mm/month (95% CI, 0.9473 to 1.3706, $p < 0.0001$). Substantial heterogeneity was observed before moderator adjustment ($\tau^2 = 0.0967$, $I^2 = 94.83\%$, $Q = 214.8914$, $p < 0.0001$).

After adjustment for force application relative to the centre of resistance and measurement method, residual heterogeneity was reduced to $\tau^2 = 0$ and $I^2 = 0.00\%$. The moderators accounted for 100.00% of between-study heterogeneity. The overall test of moderators was significant ($QM = 148.9212$, $p < 0.0001$). Residual heterogeneity was no longer statistically significant ($QE = 1.4690$, $p = 0.4797$).

Posterior tooth reference measurement with direct TAD-supported canine retraction was associated with a higher observed rate (estimate = 0.4898, 95% CI, 0.1585 to 0.8211, $p = 0.0038$). Posterior tooth reference measurement without direct TAD-supported canine retraction was associated with a

DOI: 10.17879/aods-2026-10242

Table 2. Study-level first-month canine retraction data and moderator classifications included in the meta-regression analyses.

AUTHOR (YEAR)	FORCE_CR	MEASUREMENT_BIAS	RATE_M1_MOP	SD_M1_MOP	N_M1_MOP	RATE_M1_CONTROL	SD_M1_CONTROL	N_M1_CONTROL
Alkebsi (2018)	1	0	0.65	0.26	32	0.67	0.34	32
El Awady (2019)	0	2	1.51	0.5	12	1.1	0.51	12
Feizbakhsh (2018)	0	2	1.362	0.4967	20	0.748	0.4052	20
Li (2022)	1	2	1.28	0.56	20	1.16	0.66	20
Mangal (2025)	0	canine cusp tip to mid-palatal raphe reference line	1.42	0.28	20	0.84	0.21	20
Ozkan (2021) MOP4	0	1	1.22	0.29052	12	0.88	0.19904	12
Raghav (2022)	0	canine long axis midpoint to mesial reference wire on the acrylic palatal plug	1.1164	0.486	28	0.8224	0.423	28
Thomas (2021)	0	1	1.32	0.4	30	0.86	0.4	30
Venkatachalapathy (2022)	1	3	0.6521	0.20558	20	0.37	0.08825	20

Note: *force_CR* = force application relative to the centre of resistance (1 = approximating the centre of resistance, 0 = not approximating); *measurement_bias* = reference measurement method (0 = canine displacement, 1 = posterior tooth reference with direct TAD-supported canine retraction, 2 = posterior tooth reference without direct TAD-supported retraction, 3 = lateral incisor reference); *rate_m1_mop* = first-month canine retraction rate in the MOP group (mm/month); *sd_m1_mop* = standard deviation of the first-month canine retraction rate in the MOP group; *n_m1_mop* = sample size in the MOP group; *rate_m1_control* = first-month canine retraction rate in the control group (mm/month); *sd_m1_control* = standard deviation of the first-month canine retraction rate in the control group; *n_m1_control* = sample size in the control group.

higher observed rate (estimate = 0.6300, 95% CI, 0.3686 to 0.8914, $p < 0.0001$). Other measurement categories were not statistically significant.

In the control-only model, the pooled first-month canine retraction rate was 0.8052 mm/month (95% CI, 0.6561 to 0.9542, $p < 0.0001$). Substantial heterogeneity was observed before moderator adjustment ($\tau^2 = 0.0449$, $I^2 = 93.26\%$, Q = 223.6739, $p < 0.0001$).

After adjustment for force application relative to the centre of resistance and measurement method, residual heterogeneity was reduced to $\tau^2 = 0.0053$ and $I^2 = 44.33\%$. The moderators accounted for 91.47% of between-study heterogeneity. The overall test of moderators was significant (QM = 35.9400, $p < 0.0001$). Residual heterogeneity was no longer statistically significant (QE = 4.1924, $p = 0.1229$).

Posterior tooth reference measurement with direct TAD-supported canine retraction was associated with a higher observed rate (estimate = 0.4955, 95% CI, 0.0579 to 0.9331, $p = 0.0265$). Posterior tooth reference measurement without direct TAD-supported canine retraction was associated with a higher observed rate (estimate = 0.4900, 95% CI, 0.1178 to 0.8622, $p = 0.0099$). Lateral incisor reference measurement was associated with a lower observed rate (estimate = -0.3000, 95% CI, -0.5374 to -0.0626, $p = 0.0133$). Other measurement categories were not statistically significant.

DOI: 10.17879/aods-2026-10242

4. Discussion

The present study demonstrated that between-study heterogeneity in first-month canine retraction rates following micro-osteoperforation was structured and attributable to biomechanical and measurement-related confounding factors. Adjustment for these two factors explained all between-study heterogeneity in both the acceleration model ($R^2 = 100.00\%$) and the MOP-only model ($R^2 = 100.00\%$), and most heterogeneity in the control-only model ($R^2 = 91.47\%$). The high explanatory power observed across all three perspectives suggests that force application relative to the centre of resistance and measurement methods should be standardised for future clinical trials.

Before adjustment, the observed between-study variability was statistically significant ($p < 0.0001$) and exceeded that expected from sampling error alone across all three perspectives (acceleration $Q = 39.1362$; MOP-only $Q = 214.8914$; control-only $Q = 223.6739$). These findings indicate that the apparent inconsistency among studies was not simply a consequence of random error, but reflected systematic differences in study design and outcome assessment.

After adjustment, in the acceleration model, the estimated magnitude of between-study heterogeneity in true effects decreased from $\tau = 0.1829$ mm/month before adjustment to $\tau = 0$, and I^2 decreased from 78.48% to 0.00%. These findings support the contribution of force-related and measurement-related moderators to the observed heterogeneity in treatment acceleration.

In both the acceleration model and the MOP-only model, the full moderator model was statistically significant (acceleration model: $Q_M = 24.0516$, $p < 0.0001$; MOP-only model: $Q_M = 148.9212$, $p < 0.0001$). Residual heterogeneity after moderator adjustment was no longer statistically significant in either model (acceleration model: $Q_E = 1.3457$, $p = 0.5103$; MOP-only model: $Q_E = 1.4690$, $p = 0.4797$). Together, these findings further support the role of force-related and measurement-related factors as major contributors to between-study heterogeneity.

In the control-only model, moderator adjustment also explained most of the between-study heterogeneity ($R^2 = 91.47\%$), reducing τ from 0.2119 to 0.0730 and I^2 from 93.26% to 44.33%. Although residual heterogeneity was reduced rather than fully eliminated, it was no longer statistically significant after adjustment ($Q_E = 4.1924$, $p = 0.1229$). The overall moderator test remained statistically significant ($Q_M = 35.9400$, $p < 0.0001$). These findings suggest that even baseline canine retraction rates on the control side were influenced by study design and measurement structure. However, the persistence of moderate residual I^2 in the control-only model indicates that biological variability may contribute to baseline differences in tooth movement. Therefore, untreated canine movement may reflect both methodological variation and underlying biological differences that are not fully captured by biomechanical and measurement-related moderator adjustment.

Force application relative to the centre of resistance remained an important biomechanical consideration, while it did not reach statistical significance in all three perspectives. In the acceleration model, force application approximating the centre of resistance was associated with a lower observed acceleration effect, with borderline statistical evidence ($\beta = -0.4275$ mm/month, 95% CI, -0.8715 to 0.0164; $p = 0.0591$). In the MOP-only and control-only models, the corresponding coefficients were not statistically significant. The direction of the acceleration coefficient remained consistent with the biomechanical expectation that force systems closer to the centre of resistance may reduce apparent short-term crown displacement.

This finding may be explained by the biomechanical differences between bodily and tipping movements. Bodily movement requires greater bone resorption and higher initiation forces (Lee, 1995), whereas tipping movement may produce greater apparent crown displacement over short observation intervals.

In Feizbakhsh et al. (2018), the authors stated that bodily canine movement was attempted by sliding the canine on a 0.019 × 0.025-inch stainless steel archwire in a 0.022 × 0.028-inch Roth appliance. However, under this mechanism, the retraction force was still applied from the canine bracket hook rather than near the canine centre of resistance. Therefore, although the appliance design may have reduced uncontrolled tipping, it should not be interpreted as a force system approximating the centre of resistance. The finding that between-study heterogeneity was substantially accounted for when this study was coded as not approximating the centre of resistance supports the importance of actual force proximity to the centre of resistance, rather than the intended degree of bodily movement alone.

Measurement methodology also contributed to between-study heterogeneity, particularly in combination with biomechanical factors. Among the four categories, posterior tooth reference measurements demonstrated an apparent inflation effect on canine retraction rates, especially in the MOP-only model, where posterior-tooth reference measurements were associated with higher estimated rates when direct TAD-supported canine retraction was used ($\beta = 0.4898$ mm/month, 95% CI, 0.1585 to 0.8211; $p = 0.0038$) and when direct TAD-supported canine retraction was not used ($\beta = 0.6300$ mm/month, 95% CI, 0.3686 to 0.8914; $p < 0.0001$). Fernandes et al. (2021) noted that space-closure measurements may not fully represent canine retraction, because anchorage loss may differ between experimental and control sides. Thomas et al. (2021) reported no significant change in the D2 measurement, suggesting that the first molar remained relatively stable relative to the micro-implant and that bias from mesial molar movement was minimal. However, tooth-to-tooth distance changes, compared with displacement-based measurements, may still be inflated by reciprocal movement between the canine and the posterior reference tooth, especially when canine retraction is not supported by TAD. Therefore, studies using posterior tooth or adjacent tooth references may overestimate canine movement when anchorage loss or reciprocal tooth movement is not adequately controlled.

In the acceleration and MOP-only models, lateral incisor reference measurement was associated with a higher observed acceleration effect (acceleration $\beta = 0.3021$ mm/month, 95% CI, 0.1243 to 0.4799; $p = 0.0009$; MOP $\beta = 0.0021$ mm/month, 95% CI, -0.1253 to 0.1295; $p = 0.9742$). This finding is consistent with the possibility that adjacent anterior tooth movement or tipping may have an additive effect during tooth movement rate measurement when used as the reference structure.

These findings highlight the critical role of biomechanical design and measurement structure in shaping observed treatment outcomes. Standardisation of these factors is essential for improving internal validity and enabling more robust evidence synthesis across studies. Future trials should clearly report the point of force application, the use and dimensions of power arms or auxiliary hooks, anchorage design, and the anatomical or dental reference points used for measuring canine retraction. Without such standardisation, observed differences in MOP-assisted canine retraction may reflect methodological artefacts as much as true biological or treatment effects.

5. Conclusion

Between-study heterogeneity in first-month MOP-assisted canine retraction was largely explained by force application relative to the centre of resistance and measurement methodology. Adjustment for these methodological factors explained all between-study heterogeneity in the acceleration and MOP-only models and most heterogeneity in the control-only model. These findings suggest that the apparent inconsistency among studies may reflect methodological variation rather than true differences in treatment effects.

Acknowledgements: Not applicable

Ethical approval: No ethical approval was required for this study as it did not involve human participants, animal subjects, or sensitive data. This study falls under the category of data collection without participant identification.

Consent for publication: Not applicable

Competing interests: The author(s) declare that there are no competing interests related to this work.

Authors' contributions: The author(s) declare that all the criteria for authorship designated by the International Committee of Medical Journal Editors have been met. More specifically, these are: (a) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (b) Drafting the work or revising it critically for important intellectual content; AND (c) Final approval of the version to be published; AND (d) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Declaration on AI use: The author(s) declare that no AI-assisted system was used in place of human intellectual contribution, scientific judgement, interpretation, or authorship in this manuscript. Non-substantive uses, such as language or editorial assistance, are permitted. Full responsibility for the originality, accuracy, and integrity of this work rests solely with the author(s).

References

Alikhani, M., Raptis, M., Zoldan, B., Sangsuwon, C., Lee, Y. B., Alyami, B., Corpodian, C., Barrera, L. M., Alansari, S., Khoo, E., & Teixeira, C. (2013). Effect of micro-osteoperforations on the rate of tooth movement. *American Journal of Orthodontics and Dentofacial Orthopedics*, *144*(5), 639–648. doi:10.1016/j.ajodo.2013.06.017

Alkebsi, A., Al-Maaitah, E., Al-Shorman, H., & Abu Alhaija, E. (2018). Three-dimensional assessment of the effect of micro-osteoperforations on the rate of tooth movement during canine retraction in adults with Class II malocclusion: A randomized controlled clinical trial. *American Journal of Orthodontics and Dentofacial Orthopedics*, *153*(6), 771–785. doi:10.1016/j.ajodo.2017.11.026

El Awady, A. A., Abdu Allah, K. F., & Mohammed, A. A. (2019a). Effect of flapless micro-osteoperforations on maxillary canine retraction rate and anchorage loss; a CBCT comparative study. *Ain Shams Dental Journal*, *16*(4), 145–152. doi:10.21608/ASDJ.2019.164516

El Awady, A. A., Abdu Allah, K. F., & Mohammed, A. A. (2019b). Efficacy of micro-osteoperforations on the rate of maxillary canine retraction: A randomized controlled trial. *Ain Shams Dental Journal*, *16*(4), 13–18. doi:10.21608/ASDJ.2019.164500

Feizbakhsh, M., Zandian, D., Heidarpour, M., Farhad, S. Z., & Fallahi, H. R. (2018). The use of micro-osteoperforation concept for accelerating differential tooth movement. *Journal of the World Federation of Orthodontists*, *7*(2), 56–60. doi:10.1016/j.ejwf.2018.04.002

Fernandes, L. S. D. M. C. P., Figueiredo, D. S. F., Oliveira, D. D., Houara, R. G., Rody, W. J. Jr., Gribel, B. F., & Soares, R. V. (2021). The effects of corticotomy and piezocision in orthodontic canine retraction: A randomized controlled clinical trial. *Progress in Orthodontics*, *22*(1), 37. doi:10.1186/s40510-021-00367-3

Gasparro, R., Bucci, R., De Rosa, F., Sammartino, G., Bucci, P., D'Antò, V., & Marenzi, G. (2022). Effectiveness of surgical procedures in the acceleration of orthodontic tooth movement: Findings from systematic reviews and meta-analyses. *Japanese Dental Science Review*, *58*, 137–154. doi:10.1016/j.jdsr.2022.03.003

Hashem, B. A., El-Hassanein, E. H., El-Awady, A. A., Mohamed, A. A., Hashem, M. I., Alsarani, M. M., & Hussein, F. A. (2024). Clinical evaluation of single versus repeated micro-osteoperforations during orthodontic canine retraction: A randomized clinical trial. *Cureus*, *16*(1), e52026. doi:10.7759/cureus.52026

Lee, B. W. (1995). The force requirements for tooth movement Part I: Tipping and bodily movement. *Australian Orthodontic Journal*, *13*, 238–248. doi:10.2478/aoj-1995-0004

Li, J., Papadopoulou, A. K., Gandedkar, N., Dalci, K., Darendeliler, M. A., & Dalci, O. (2022). The effect of micro-osteoperforations on orthodontic space closure investigated over 12 weeks: A split-mouth, randomized controlled clinical trial. *European Journal of Orthodontics*, *44*(4), 427–435. doi:10.1093/ejo/cjab079

Mangal, R., & Yadav, V. (2025). Comparative rate of canine retraction: Miniscrew-assisted micro-osteoperforations versus conventional sliding mechanics. *International Journal of Life Sciences, Biotechnology and Pharma Research*, *14*(12), 274–278. doi:10.69605/ijlbpr_14.12.2025.48

Ozkan, T. H., & Arici, S. (2021). The effect of different micro-osteoperforation depths on the rate of orthodontic tooth movement: A single-center, single-blind, randomized clinical trial. *The Korean Journal of Orthodontics*, *51*(3), 157–165. doi:10.4041/kjod.2021.51.3.157

Raghav, P., Khera, A. K., Preeti, P., Jain, S., Mohan, S., & Tiwari, A. (2022). Effect of micro-osteoperforations on the rate of orthodontic tooth movement and expression of biomarkers: A randomized controlled clinical trial. *Dental Press Journal of Orthodontics*, *27*(1), e2219403. doi:10.1590/2177-6709.27.1.e2219403.oar

Ribeiro, G. L., & Jacob, H. B. (2016). Understanding the basis of space closure in orthodontics for a more efficient orthodontic treatment. *Dental Press Journal of Orthodontics*, *21*(2), 115–125. doi:10.1590/2177-6709.21.2.115-125.sar

Sivarajan, S., Doss, J. G., Papageorgiou, S. N., Cobourne, M. T., & Wey, M. C. (2019). Mini-implant supported canine retraction with micro-osteoperforation: A split-mouth randomized clinical trial. *The Angle Orthodontist*, *89*(2), 183–189. doi:10.2319/011518-47.1

Teixeira, C. C., Khoo, E., Tran, J., Chartres, I., Liu, Y., Thant, L. M., Khabensky, I., Gart, L. P., Cisneros, G., & Alikhani, M. (2010). Cytokine expression and accelerated tooth movement. *Journal of Dental Research*, *89*(10), 1135–1141. doi:10.1177/0022034510373764

Thomas, S., Das, S. K., Barik, A. K., Raj, S. C., Rajasekaran, A., & Mishra, M. (2021). Evaluation of physiodispenser-assisted micro-osteoperforation on the rate of tooth movement and associated periodontal tissue status during individual canine retraction in first premolar extraction cases: A split-mouth randomized controlled clinical trial. *Journal of the World Federation of Orthodontists*, *10*(3), 89–97. doi:10.1016/j.ejwf.2021.05.001

Venkatachalapathy, S., Natarajan, R., Ramachandran, U. M., Rajakumar, P., Rangarajan, S., Patil, D., & Manickavasagam, V. (2022). Effect of frequency of micro-osteoperforation on miniscrew-supported canine retraction: A single-centered, split-mouth randomized controlled trial. *The Journal of Contemporary Dental Practice*, *23*(8), 781–787.

Wilcko, W. M., Wilcko, T., Bouquot, J. E., & Ferguson, D. J. (2001). Rapid orthodontics with alveolar reshaping: Two case reports of decrowding. *International Journal of Periodontics and Restorative Dentistry*, *21*(1), 9–19.

DOI: 10.17879/aods-2026-10242