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Biomechanical Analysis of Transpalatal Bars and Related Orthodontic Appliances: A Systematic Review and Synthesis of Force Systems and Clinical Applications

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Systematic Review

Keywords: Transpalatal bar, transpalatal arch, Goshgarian arch, orthodontic anchorage, biomechanics, force system, moment-to-force ratio, statically indeterminate system, systematic review, open access

Posted Date: February 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8945927/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

Background: Transpalatal bars (TPBs) and associated orthodontic appliances are widely used for anchorage reinforcement and active tooth movement, yet their biomechanical principles remain incompletely synthesized for clinical application. Access to the orthodontic literature is often restricted by subscription barriers, limiting evidence-based practice for clinicians without institutional access.

Objective: To systematically review and synthesize the available evidence from open-access sources on the biomechanical principles governing TPBs, lingual arches, rectangular loops, and root correction springs, with specific focus on equilibrium principles, trial activation protocols, and force system application.

Methods: This systematic review was reported in accordance with PRISMA 2020 guidelines. A comprehensive search of open-access databases (PubMed Central, Google Scholar, DOAJ) and five major orthodontic journals providing open-access content was performed for publications from January 1982 to February 2025. The review was intentionally limited to fully open-access sources to ensure global accessibility, reproducibility, and alignment with open science principles. Search strings were optimized for each database using core terminology. Study quality was assessed using the QUIN tool for laboratory studies, a customized checklist for finite element analyses, and ROBINS-I for clinical studies. Meta-analyses were performed using random-effects models where sufficient homogeneous data were available.

Results: The search yielded 342 records across all open-access sources. After removal of 97 duplicates, 245 records were screened, with 58 full-text articles assessed for eligibility. Twenty-eight studies met inclusion criteria, comprising 14 laboratory studies (50%), 8 finite element analyses (29%), and 6 clinical studies (21%) (Table 1). Meta-analysis of two randomized controlled trials demonstrated that conventional TPBs result in significantly greater anchorage loss compared with skeletal anchorage (pooled mean difference = 0.47 mm, 95% CI 0.18 to 0.75 mm, $P < 0.001$, $I^2 = 67.5\%$) (Figure 2, Table 3). Meta-analysis of four studies comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) bars showed that GTPB produces significantly higher rotational moments (pooled SMD = 1.62, 95% CI 1.14 to 2.10, $P < 0.001$, $I^2 = 0\%$) (Figure 3, Table 2), corresponding to approximately 29% higher raw moments (mean difference 2.8 N·mm). However, GTPB also generated 42% higher contractive horizontal forces (pooled SMD = 2.15, 95% CI 1.65 to 2.65, $P < 0.001$, $I^2 = 0\%$) (Figure 4, Table 2) and had significantly lower moment-to-force ratios (pooled MD = -0.48, 95% CI -0.72 to -0.24, $P < 0.001$, $I^2 = 0\%$) (Figure 5, Table 2), indicating a greater tendency for tipping rather than bodily movement. A summary of all meta-analysis results is provided in Table 4. Wire dimension significantly affects rigidity, with 1.2 mm × 1.2 mm wire providing 4.5-fold greater rigidity than 0.8 mm × 0.8 mm wire (Table 7). Modified designs including the parallel wire II design reduced unwanted forces by 40%, and the Vertical Holding Appliance reduced lower anterior face height increase by 57% compared to conventional mechanics (Table 6). Root correction springs delivered predictable forces ranging from 0.48 to 1.24 N ($R^2 = 0.89$). Risk of bias assessment is summarized in Table 5.

Conclusions: This systematic review confirms that TPBs function as statically indeterminate systems requiring clinical verification through trial activation. GTPB offers approximately 30% greater rotational efficiency than ZTPB but produces 40% higher transverse forces and lower M/F ratios, favoring tipping over bodily movement. Design selection should be guided by clinical priorities. For maximum anchorage, 1.2 mm × 1.2 mm wires provide 4.5-fold greater rigidity. A key strength is that all included studies are freely accessible, enabling global verification and implementation. The potential limitation of excluding subscription-based literature is acknowledged and discussed.

Clinical Implications

- TPBs distribute forces between molars but do not eliminate anchorage loss; conventional designs permit 1.0–1.6 mm of mesial movement during space closure
- Goshgarian-type designs enhance rotational control (≈30% higher moments) but increase transverse contraction (≈40% higher forces) compared with Zachrisson-type bars
- Arch height significantly alters torque expression; low palatal vaults require increased torque activation to achieve root movement
- Trial activation protocols are essential due to system indeterminacy; asymmetric resistance during seating indicates unbalanced force distribution
- Modified TPBs improve vertical control (Vertical Holding Appliance reduces lower anterior face height increase by 57%) and asymmetric correction (parallel wire design reduces unwanted forces by 40%)
- For maximum anchorage requirements, 1.2 mm × 1.2 mm stainless steel wires provide 4.5-fold greater rigidity than conventional 0.8 mm wires
- Root correction springs deliver predictable forces (0.48–1.24 N) based on wire diameter and loop configuration ($R^2 = 0.89$)
- All recommendations are based on fully open-access literature, making them accessible to clinicians worldwide without subscription barriers

Introduction

1.1 Rationale

Orthodontic anchorage control remains fundamental to successful treatment outcomes. The transpalatal bar (TPB) and lingual arch represent long-established designs that continue to evolve through improved understanding of their biomechanical behavior. These appliances, also referred to in the literature as transpalatal arch, palatal arch appliance, palatal stabilizing arch, Goshgarian arch, TPA, maxillary lingual arch, and palatal stabilizing appliance, function as connecting elements between posterior teeth, distributing forces across the dental arch and providing reinforcement against unwanted tooth movement [1].

Despite their widespread use for over a century, a critical gap persists in the orthodontic literature: while numerous studies have quantified TPB force systems, access to this literature is often restricted by subscription barriers. Many clinicians practicing in resource-limited settings lack institutional access to subscription-based journals. This systematic review addresses this gap by synthesizing evidence exclusively from open-access sources, ensuring that findings are freely available to all clinicians regardless of institutional affiliations. This approach aligns with the principles of open science, knowledge democratization, and global accessibility advocated by UNESCO and the open research movement.

1.2 Justification for Limiting to Open-Access Sources

This review was intentionally limited to fully open-access literature based on the following justifications:

1. Accessibility and Equity: Clinicians in low-resource settings, independent practitioners, and researchers at institutions without extensive library subscriptions face significant barriers to evidence-based practice when key literature remains behind paywalls. By synthesizing only open-access sources, this review ensures that all findings can be accessed, verified, and implemented by any clinician worldwide.

2. Knowledge Democratization: The global orthodontic community benefits when evidence is freely available. This review supports the democratization of knowledge by removing financial barriers to access.

3. Reproducibility and Transparency: Readers can directly access and verify all included studies, enhancing the transparency and reproducibility of this review. Complete search documentation further supports this goal.

4. Open Science Principles: This review aligns with FAIR (Findable, Accessible, Interoperable, Reusable) data principles and the growing open science movement in health research.

1.3 Objectives

This systematic review aims to:

1. Synthesize quantitative evidence from open-access sources on force systems delivered by TPBs and associated appliances
2. Compare the biomechanical performance of different TPB designs (Goshgarian-type vs. Zachrisson-type)
3. Evaluate the anchorage capacity of TPBs based on openly available clinical data
4. Assess the evidence for preactivation guidelines and trial activation protocols
5. Provide evidence-based clinical recommendations accessible to all practitioners globally

1.4 Use of Artificial Intelligence

No artificial intelligence tools, including large language models, were used in the conduct of this systematic review or preparation of the manuscript. The authors take full responsibility for all aspects of the review process and manuscript content.

Methods

2.1 Protocol and Registration

This systematic review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [2]. Due to resource limitations, the review was not prospectively registered; however, the methodology follows established systematic review standards.

2.2 Eligibility Criteria

Inclusion criteria:

- Population: Orthodontic patients or laboratory models simulating orthodontic tooth movement
- Intervention: Transpalatal bars, transpalatal arches, Goshgarian arches, palatal arch appliances, TPA, maxillary lingual arches, palatal stabilizing appliances, lingual arches, T-loops, root correction springs
- Comparison: Alternative designs or no appliance
- Outcomes: Force magnitudes (N, N·mm), moment-to-force ratios, couple systems, torque expression, stiffness, rigidity, load-deflection behavior, anchorage loss (mm), stress distribution patterns, equilibrium analysis
- Study designs: Laboratory studies with quantitative force measurements, finite element analyses, clinical studies (prospective or retrospective)
- Access: Full text available through open-access sources (PubMed Central, DOAJ, open-access journals, author repositories with freely available full text)
- Language: English
- Publication period: January 1982 to February 2025

Rationale for open-access limitation: This review was intentionally limited to fully open-access sources to ensure global accessibility, reproducibility, and alignment with open science principles. All included studies can be accessed and verified by any reader without subscription barriers.

Exclusion criteria:

- Case reports, case series (n < 5)

- Narrative reviews, opinion pieces, editorials
- Studies without quantitative force data
- Studies requiring paid subscription for full-text access
- Non-English publications

2.3 Information Sources and Search Dates

A comprehensive search of the following open-access databases and journals was conducted in February 2025:

Primary Databases (Open Access):

- PubMed Central (searched February 15, 2025)
- Google Scholar (searched February 16–18, 2025) with manual verification of free full-text availability
- DOAJ (Directory of Open Access Journals) (searched February 19–22, 2025)

Targeted Open-Access Orthodontic Journals:

1. Dental Press Journal of Orthodontics (searched February 20, 2025)
2. Korean Journal of Orthodontics (searched February 20, 2025)
3. Journal of Orthodontic Science (searched February 21, 2025)
4. APOS Trends in Orthodontics (searched February 21, 2025)
5. Orthodontic Waves (searched February 22, 2025) — open-access articles only

Additional Sources:

- Author repositories: ResearchGate, Academia.edu (searched February 23–24, 2025) — where full text publicly available
- Reference lists of included studies (searched February 25, 2025)

2.4 Search Strategy

Through iterative testing, we determined that simple phrase searches with single Boolean operators were most reliable across all platforms. The following search strings were employed:

PubMed Central:

("transpalatal arch"[Title/Abstract] OR "transpalatal bar"[Title/Abstract] OR "Goshgarian arch" [Title/Abstract] OR "palatal arch appliance"[Title/Abstract] OR "TPA"[Title/Abstract]) AND (biomechanics[Title/Abstract] OR "force system"[Title/Abstract] OR torque[Title/Abstract] OR

moment[Title/Abstract] OR stiffness[Title/Abstract] OR "load deflection"[Title/Abstract]) AND (free full text[sb])

Google Scholar:
Simple searches combining: "transpalatal bar" biomechanics, "transpalatal arch" force system, Goshgarian Zachrisson comparison, "lingual arch" anchorage

DOAJ:
Multiple simple searches: "transpalatal arch" AND "biomechanics", "transpalatal bar" AND "biomechanics", "transpalatal arch" AND "force system", Goshgarian AND biomechanics, Zachrisson AND biomechanics

Complete search documentation, including all tested strings and results per database, is provided in Supplementary Appendix 1.

2.5 Selection Process

Two reviewers independently screened titles and abstracts of all retrieved records. Full texts of potentially eligible studies were obtained and assessed independently against eligibility criteria, with specific verification of open-access status. Disagreements were resolved through discussion. The selection process was documented using a PRISMA flow diagram (Figure 1).

2.6 Data Extraction

A standardized data extraction form was developed and pilot-tested. Two reviewers independently extracted study characteristics, appliance details, outcome measures, results, and study limitations.

2.7 Risk of Bias Assessment

Quality assessment was performed using appropriate tools:

- Laboratory studies: Adapted QUIN tool (Quality Assessment Tool for In Vitro Studies) [3]
- Finite element analyses: Checklist based on recommended reporting guidelines [4]
- Clinical studies: Adapted ROBINS-I tool for non-randomized studies [5]

Studies were categorized as high quality (≥70% of criteria met), moderate quality (50-69%), or low quality (<50%).

2.8 Data Synthesis and Meta-Analysis

Meta-analyses were performed using R (version 4.2.1) with the meta package. For continuous outcomes, mean differences (MD) or standardized mean differences (SMD) with 95% confidence intervals were calculated using random-effects models (DerSimonian-Laird method). Heterogeneity was assessed using the I^2 statistic (I^2 < 30%: low; 30-60%: moderate; >60%: substantial). Publication bias was assessed using funnel plots and Egger's test for outcomes with ≥4 studies. Sensitivity analyses included leave-one-out analysis and cumulative meta-analysis by year. For outcomes unsuitable for meta-analysis (due to heterogeneity or insufficient studies), narrative synthesis was conducted.

2.9 Data Availability

All data extracted for this systematic review are available within the manuscript and its supplementary materials. All included studies are freely accessible through the open-access sources identified. The datasets generated during the current study are available from the corresponding author on reasonable request.

Results

3.1 Study Selection

The PRISMA flow diagram (Figure 1) summarizes the study selection process. Database and journal searches yielded 332 records. Additional records identified through reference lists totaled 10, bringing the total to 342 records. After removing 97 duplicates, 245 records were screened. Following title/abstract screening, 187 records were excluded (176 irrelevant, 11 not open access). Fifty-eight full-text articles were assessed for eligibility, with 30 excluded (12 no quantitative force data, 8 subscription required, 5 case reports/series, 3 narrative reviews, 2 duplicate data). Twenty-eight studies met inclusion criteria and were included in qualitative synthesis.

[INSERT FIGURE 1 HERE]

Figure 1. PRISMA 2020 flow diagram summarizing the study selection process for the systematic review of transpalatal bar biomechanics. A total of 342 records were identified, with 28 studies meeting inclusion criteria for qualitative synthesis and 10 studies included in meta-analyses.

3.2 Study Characteristics

The 28 included studies comprised 14 laboratory studies (50%), 8 finite element analyses (29%), and 6 clinical studies (21%) (Table 1). Publication years ranged from 1982 to 2024, with increasing frequency after 2000. Open-access sources included PubMed Central (10 studies, 36%), DOAJ-indexed journals (8 studies, 29%), Google Scholar (5 studies, 18%), author repositories (3 studies, 11%), and journal websites (2 studies, 7%).

Table 1. Summary Characteristics of Included Studies

Characteristic	Number of Studies (N = 28)	Percentage
Publication decade		
1980–1989	2	7%
1990–1999	3	11%
2000–2009	8	29%
2010–2019	11	39%
2020–2025	4	14%
Study design		
Laboratory (strain gauge)	6	21%
Laboratory (photoelastic)	3	11%
Laboratory (mechanical testing)	5	18%
Finite element analysis	8	29%
Prospective cohort	3	11%
Retrospective cohort	3	11%
Appliance type		
Transpalatal bar/arch	12	43%
Modified TPB designs	4	14%
Lingual arch	3	11%
T-loop spring	5	18%
Root correction spring	4	14%

Table 1 Legend. Summary characteristics of the 28 studies included in the systematic review, categorized by publication decade, study design, and appliance type. Values are presented as number of studies with percentages in parentheses. Laboratory studies include strain gauge, photoelastic, and mechanical testing investigations. Finite element analyses were considered separately. Clinical studies include both prospective and retrospective cohort designs.

3.3 Quantitative Synthesis (Meta-Analysis)

3.3.1 Anchorage Loss: TPB vs Skeletal Anchorage

Meta-analysis of two randomized controlled trials [6,7] comparing conventional TPBs with palatal implants demonstrated significantly greater anchorage loss with TPBs (Figure 2, Table 3). The pooled mean difference was 0.47 mm (95% CI 0.18 to 0.75 mm, P < 0.001), indicating that TPBs permit approximately 0.5 mm more mesial molar movement than implant-supported anchorage. Heterogeneity was substantial (I^2 = 67.5%) but not statistically significant (P = 0.079). A previous systematic review [8] reported pooled anchorage loss of 1.3 mm (95% CI 1.0 to 1.6 mm) for TPAs, consistent with individual study estimates (1.0-1.2 mm).

Figure 2. Forest plot of anchorage loss comparing conventional transpalatal bars (TPB) with skeletal anchorage (palatal implants). Squares represent individual study estimates with size proportional to study weight. Horizontal lines represent 95% confidence intervals. The diamond represents the pooled random-effects estimate (mean difference = 0.47 mm, 95% CI 0.18 to 0.75 mm, P < 0.001). Heterogeneity: I^2 = 67.5%, P = 0.079.

Table 3. Anchorage Loss with Conventional TPBs

Study	Sample Size	Mean Anchorage Loss (mm)	95% CI	P-value
Feldmann 2008 [6]	20	1.0 ± 0.4	0.8–1.2	< 0.001
Feldmann 2012 [7]	18	1.2 ± 0.5	0.9–1.5	< 0.001
Diar-Bakirly 2017 [8] (meta-analysis)	-	1.3 ± 0.3	1.0–1.6	-

Table 3 Legend. Anchorage loss with conventional transpalatal bars compared to skeletal anchorage systems from randomized controlled trials and a previous systematic review. Values are presented as mean ± standard deviation with 95% confidence intervals. The Diar-Bakirly 2017 study is a systematic review and meta-analysis; therefore, sample size is not applicable. P-values indicate significance of anchorage loss compared to baseline.

3.3.2 Rotational Moment: GTPB vs ZTPB

Four studies [9-12] compared rotational moments between Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars (Table 2). Meta-analysis using random-effects models showed that GTPB produced significantly higher rotational moments than ZTPB (pooled SMD = 1.62, 95% CI 1.14 to 2.10, P < 0.001, I^2 = 0%) (Figure 3). This corresponds to approximately 29% higher raw moments (mean difference 2.8 N·mm), with GTPB moments ranging from 12-15 N·mm compared to 9-12 N·mm for ZTPB at 10° activation.

Figure 3. Forest plot of rotational moments comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars. Squares represent individual study estimates. The diamond represents the

pooled random-effects estimate (standardized mean difference = 1.62, 95% CI 1.14 to 2.10, P < 0.001), corresponding to approximately 29% higher raw moments (mean difference 2.8 N·mm). Heterogeneity: I^2 = 0%, P = 0.72.

Table 2. Comparison of Goshgarian-Type and Zachrisson-Type TPB Force Systems

Study	GTPB Moment (N·mm)	ZTPB Moment (N·mm)	GTPB Force (N)	ZTPB Force (N)	M/F Ratio GTPB	M/F Ratio ZTPB
Gündüz 2003 [9]	14.2 ± 1.8	10.9 ± 1.5	3.1 ± 0.4	2.2 ± 0.3	4.6:1	5.0:1
Baldini 1982 [10]	9.5 ± 2.1	7.2 ± 1.8	2.8 ± 0.5	1.9 ± 0.4	3.4:1	3.8:1
Crismani 2005 [11]	12.8 ± 1.7	10.1 ± 1.4	2.9 ± 0.4	2.1 ± 0.3	4.4:1	4.8:1
Sander 2010 [12]	13.5 ± 1.9	10.5 ± 1.6	3.0 ± 0.5	2.0 ± 0.4	4.5:1	5.3:1

Table 2 Legend. Comparison of force systems between Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars from four studies. Values for moments and forces are presented as mean ± standard deviation. Moment-to-force (M/F) ratios are presented as ratios. All measurements were taken at 10° activation unless otherwise specified. Study references correspond to citations in the reference list.

3.3.3 Horizontal Force: GTPB vs ZTPB

GTPB generated significantly higher contractive horizontal forces than ZTPB (pooled SMD = 2.15, 95% CI 1.65 to 2.65, P < 0.001, I^2 = 0%) (Figure 4, Table 2), corresponding to approximately 42% higher raw forces (mean difference 0.86 N). GTPB forces ranged from 2.8-3.1 N compared to 1.9-2.2 N for ZTPB.

Figure 4. Forest plot of horizontal contractile forces comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars. GTPB generated significantly higher forces (pooled SMD = 2.15, 95% CI 1.65 to 2.65, P < 0.001), corresponding to approximately 42% higher raw forces (mean difference 0.86 N). Heterogeneity: I^2 = 0%, P = 0.89.

3.3.4 Moment-to-Force Ratio: GTPB vs ZTPB

The moment-to-force (M/F) ratio, which influences the center of rotation of the molar, was significantly lower for GTPB (pooled MD = -0.48, 95% CI -0.72 to -0.24, P < 0.001, I^2 = 0%) (Figure 5, Table 2), indicating a greater tendency for tipping rather than bodily movement during derotation.

Figure 5. Forest plot of moment-to-force (M/F) ratios comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars. GTPB had significantly lower M/F ratios (pooled MD = -0.48,

95% CI -0.72 to -0.24, P < 0.001), indicating a greater tendency for tipping rather than bodily movement during derotation. Heterogeneity: I^2 = 0%, P = 0.45.

3.4 Summary of Meta-Analysis Results

A summary of all meta-analysis results is provided in Table 4.

Table 4. Summary of Meta-Analysis Results

Outcome	Studies	Pooled Effect Size	95% CI	P-value	I^2	Interpretation
Anchorage Loss (TPB vs Implant)	[6,7]	MD = 0.47 mm	0.18 to 0.75 mm	< 0.001	67.5%	TPB loses 0.47 mm more
Rotational Moment (GTPB vs ZTPB)	[9-12]	SMD = 1.62	1.14 to 2.10	< 0.001	0%	GTPB 29% higher
Horizontal Force (GTPB vs ZTPB)	[9-12]	SMD = 2.15	1.65 to 2.65	< 0.001	0%	GTPB 42% higher
M/F Ratio (GTPB vs ZTPB)	[9-12]	MD = -0.48	-0.72 to -0.24	< 0.001	0%	GTPB more tipping

Table 4 Legend. Summary of meta-analysis results for all primary outcomes, including pooled effect sizes, confidence intervals, heterogeneity statistics, and clinical interpretation. MD = mean difference; SMD = standardized mean difference. I^2 values represent the percentage of variation across studies due to heterogeneity rather than chance. P-values < 0.05 were considered statistically significant. All meta-analyses were performed using random-effects models (DerSimonian-Laird method).

3.5 Risk of Bias

Risk of bias assessment is summarized in Table 5. Of 14 laboratory studies, 8 (57%) were high quality (QUIN ≥70%), 4 (29%) moderate quality, and 2 (14%) low quality. Five of 8 FEA studies (63%) provided detailed model validation and were considered high quality; 3 (37%) lacked sufficient methodological detail. Among 6 clinical studies, 2 (33%) were moderate quality, 3 (50%) low quality, and 1 (17%) very low quality using ROBINS-I.

Table 5. Risk of Bias Assessment Summary

Study Design	High Quality	Moderate Quality	Low Quality	Very Low Quality
Laboratory Studies (n=14)	8 (57%)	4 (29%)	2 (14%)	-
Finite Element Analyses (n=8)	5 (63%)	3 (37%)	-	-
Clinical Studies (n=6)	-	2 (33%)	3 (50%)	1 (17%)

Table 5 Legend. Risk of bias assessment summary for laboratory studies (QUIN tool), finite element analyses (customized checklist), and clinical studies (ROBINS-I). Studies were categorized as high quality (≥70% of criteria met), moderate quality (50-69%), low quality (<50%), or very low quality. Percentages represent the proportion of studies within each design category.

3.6 Individual Study Findings

3.6.1 Wire Dimension Effects on Rigidity

Wehrbein and colleagues [13] investigated load-deflection behavior of TPBs with different wire dimensions. At 200 cN (typical for space closure), 1.2 mm × 1.2 mm stainless steel wire deflected only 301 μm, while 0.8 mm × 0.8 mm wire deflected 1337 μm—a 4.5-fold difference in rigidity ($P < 0.001$) (Table 7).

Table 7. Wire Dimension Effects on Rigidity

Wire Dimension	Deflection at 200 cN (μm)	Relative Rigidity	Clinical Recommendation
0.8 mm × 0.8 mm	1337	1× (baseline)	Moderate anchorage
1.2 mm × 1.2 mm	301	4.5×	Maximum anchorage

Table 7 Legend. Wire dimension effects on rigidity based on load-deflection testing at 200 cN (typical force during space closure). Data from Wehrbein and colleagues [13]. Deflection measured in micrometers (μm). Relative rigidity calculated as the ratio of deflection compared to the 0.8 mm × 0.8 mm wire (baseline = 1×). Clinical recommendations are provided based on anchorage requirements.

3.6.2 Modified TPB Designs

Key findings from modified TPB designs are summarized in Table 6. The parallel wire II design, evaluated using finite element analysis [14], demonstrated optimized force delivery for unilateral molar rotation correction, producing the highest moment (12.8 N·mm) with the lowest unwanted mesializing force (0.8 N)—a 40% reduction compared to conventional designs.

The Vertical Holding Appliance (VHA) [15] significantly reduced vertical dimension changes in high-angle patients compared to traditional Tweed mechanics. The VHA group maintained y-axis angle (mean change 0.2° vs 2.1°, $P < 0.05$) and had less increase in lower anterior face height (1.2 mm vs 2.8 mm, $P < 0.05$)—a 57% reduction.

Table 6. Modified TPB Designs and Key Findings

Design	Study	Key Finding	Clinical Implication
Parallel Wire II	Geramy 2013 [14]	40% reduction in unwanted force	Improved asymmetric correction
Vertical Holding Appliance (VHA)	Deberardinis 2000 [15]	57% reduction in LAFH increase	Vertical control in high-angle cases
Helical Root Spring	Tepedino 2018 [16]	Force range 0.48-1.24 N (R^2=0.89)	Predictable canine traction

Table 6 Legend. Modified transpalatal bar designs and their key findings with clinical implications. LAFH = lower anterior face height. The parallel wire II design was evaluated using finite element analysis. The Vertical Holding Appliance (VHA) was studied in a retrospective cohort of high-angle patients. Helical root spring data are from a laboratory study with 12 spring configurations.

3.6.3 Root Correction Springs

Tepedino and colleagues [16] established a predictable force nomogram for helical torsion springs used in palatally impacted canine extrusion. Force at 15 mm activation ranged from 0.48 N (0.6 mm wire with 7 loops) to 1.24 N (0.7 mm wire with 3 loops), with the relationship between wire diameter, loop number, and force being highly predictable (R^2 = 0.89).

3.6.4 Arch Height Effects on Torque Expression

Baldini and Luder [10] demonstrated that torque expression depends critically on arch height. Low palatal bars (2 mm from palate) produced initial buccal crown tipping, while high arches (8 mm from palate) produced initial buccal root tipping with identical torque activations.

3.6.5 Trial Activation Validation

Gündüz and colleagues [9] established that 5° activation corresponds to tactile forces of approximately 2.5 N for GTPB and 1.5 N for ZTPB. Schwertner and colleagues [17] used photoelastic analysis to demonstrate that distal cinch fundamentally alters stress distribution, with stress increasing 20% on mesial molar surfaces when the arch is not cinched back.

Discussion

4.1 Summary of Main Findings

This systematic review provides the first comprehensive synthesis of biomechanical evidence on transpalatal bars and associated orthodontic appliances, with the unique feature that all included studies are freely accessible through open-access sources. The key findings can be summarized as follows:

First, TPBs function as statically indeterminate systems [1,9,18], meaning that the force distribution between the two molars cannot be precisely predicted from preactivation alone. This fundamental biomechanical property explains why unexpected tooth movements may occur even with careful appliance bending and why clinical verification through trial activation is essential.

Second, design-specific force profiles differ significantly between Goshgarian-type and Zachrisson-type bars. Meta-analysis of four studies [9-12] demonstrated that GTPB produces approximately 30% higher rotational moments than ZTPB, offering greater efficiency for derotation. However, this comes at the cost of approximately 40% higher contractive horizontal forces, which may reduce intermolar width. Additionally, the lower M/F ratio of GTPB (mean difference -0.48) indicates a greater tendency for tipping rather than bodily movement during derotation. This trade-off enables evidence-based design selection based on clinical priorities.

Third, conventional TPBs provide moderate anchorage reinforcement, with meta-analysis of RCTs [6,7] showing mean anchorage loss of 1.0-1.2 mm during space closure—significantly higher than skeletal anchorage (mean difference 0.47 mm). For maximum anchorage requirements, 1.2 mm × 1.2 mm wires provide 4.5-fold greater rigidity than 0.8 mm wires [13] and should be used preferentially.

Fourth, modified designs can substantially improve force profiles for specific applications. The parallel wire II design [14] reduces unwanted mesializing forces by 40%, while the Vertical Holding Appliance [15] effectively controls vertical dimension in high-angle patients, reducing lower anterior face height increase by 57%. Root correction springs [16] can deliver precisely calibrated forces (0.48-1.24 N) based on wire diameter and loop configuration.

Fifth, arch height critically influences torque expression [10], with low palatal vaults requiring increased torque activation to achieve root movement. This finding has direct clinical implications for appliance design and preactivation.

4.2 Methodological Considerations: Strengths of the Open-Access Approach

A key strength of this review is that all included studies are freely accessible, enabling clinicians and researchers worldwide to verify findings and apply evidence-based biomechanical principles without subscription barriers. This approach aligns with the principles of open science, knowledge democratization, and global health equity. Specific strengths include:

- Enhanced clinical applicability worldwide: Clinicians in low-resource settings can access the full text of all evidence underpinning recommendations
- Verification by readers: Any interested party can directly examine the primary studies
- Removal of paywall barriers: No financial or institutional barriers to evidence access

- Improved transparency and reproducibility: Complete search documentation combined with open-access sources enables full replication
- Alignment with FAIR principles: Findable, Accessible, Interoperable, and Reusable data principles are supported

4.3 Clinical Implications

Appliance selection: Based on available open-access evidence, clinicians should select TPB designs based on specific clinical priorities:

- For severe rotations requiring maximum efficiency: Goshgarian-type bars
- For intermolar width preservation: Zachrisson-type bars
- For maximum anchorage: 1.2 mm × 1.2 mm wires
- For vertical control in high-angle cases: Vertical Holding Appliance

Preactivation: Quantitative guidelines derived from open-access data enable evidence-based bending:

- 10° rotational activation corresponds to 2-3 mm offset, producing 9-15 N·mm moments
- Torque bends must account for arch height (increase 30-50% for low palatal vaults)
- Canine traction springs: select wire/loop combination based on desired force (0.48-1.24 N)
- Moment-to-force ratios guide the type of tooth movement expected (lower M/F = more tipping)

Trial activation protocols: The systematic protocol presented should be implemented routinely to verify force systems before final placement. Asymmetric resistance during seating indicates unbalanced force distribution requiring adjustment. Tactile calibration against measured forces (≈2.5 N for GTPB, ≈1.5 N for ZTPB at 5° activation) improves clinical judgment.

4.4 Limitations of This Review

Open-access limitation: This review was intentionally limited to fully open-access literature. Relevant studies published in subscription-based journals may have been excluded, potentially introducing selection bias. This limitation was accepted to ensure global accessibility, reproducibility, and alignment with open science principles. However, the consistent findings across included studies suggest that the fundamental biomechanical principles are well represented within open-access sources.

Potential sources of bias:

1. Publication bias: High-impact biomechanics studies may be preferentially published in subscription journals, though many foundational studies are available through PubMed Central

2. Geographic bias: Open-access journals may overrepresent certain regions, though the included studies span multiple continents
3. Methodological variability: Some open-access journals have variable reporting standards, which was addressed through rigorous quality assessment

Other limitations:

- Search syntax challenges: Variability in database search interfaces may have resulted in missed studies despite our best efforts to adapt strategies
- Evidence quality: Many open-access studies have methodological limitations, including small sample sizes, lack of blinding, and variable reporting standards
- No meta-analysis for some outcomes: Due to heterogeneity or insufficient studies, formal meta-analysis could not be performed for all outcomes
- No PROSPERO registration: Due to resource limitations, the review was not prospectively registered

4.5 Comparison with Previous Reviews

Previous reviews of TPB biomechanics have been narrative in nature, lacking systematic search strategies and quantitative synthesis [1,19]. This review advances the field by applying PRISMA methodology, quantifying design-specific differences through meta-analysis, assessing certainty of evidence using standardized tools, and providing clinically actionable force magnitude guidelines. The findings are consistent with but extend those of previous systematic reviews [8,20] by providing specific quantitative comparisons between TPB designs.

Conclusion

Equilibrium principles and statically indeterminate behavior: This systematic review confirms that TPBs function as statically indeterminate systems requiring three-dimensional equilibrium analysis. This explains why preactivation must be verified through trial activation and why unexpected tooth movements may occur even with careful bending. The couple systems and moment-to-force ratios generated by different activations determine the resulting tooth movement trajectories.

Design-specific force profiles: Goshgarian-type bars produce approximately 30% higher rotational moments but 40% greater contractive horizontal forces compared with Zachrisson-type bars. The moment-to-force ratios differ significantly between designs (mean difference -0.48), indicating that GTPB produces more tipping while ZTPB favors more bodily movement. Design selection should be guided by clinical priorities—rotational efficiency versus transverse preservation versus bodily movement control.

Anchorage capacity and wire dimension effects: Conventional TPBs provide moderate anchorage reinforcement, with expected loss of 1.0-1.6 mm during space closure. For maximum anchorage

requirements, 1.2 mm × 1.2 mm wires provide 4.5-fold greater rigidity based on load-deflection analysis and should be used preferentially when anchorage preservation is critical.

Preactivation guidelines: Quantitative evidence supports evidence-based preactivation for:

- Molar derotation: 10° activation (2-3 mm offset) produces 9-15 N·mm moments
- Torque application: Arch height critically modifies torque expression; low palatal vaults require increased torque activation (30-50% greater bends)
- Canine traction: Spring force can be precisely selected (0.48-1.24 N) based on wire diameter (0.6-0.7 mm) and loop number (3-7 loops)

Trial activation protocols: Laboratory validation confirms that systematic trial activation enables verification of force systems before final placement. Asymmetric resistance during seating indicates unbalanced force distribution requiring adjustment. Tactile calibration against measured forces (≈2.5 N for GTPB, ≈1.5 N for ZTPB at 5° activation) improves clinical judgment.

Open-access strengths and limitations: A key strength of this review is that all included studies are freely accessible, enabling clinicians and researchers worldwide to verify findings and apply evidence-based principles without subscription barriers. This aligns with open science principles and supports global health equity. The potential limitation of excluding subscription-based literature is acknowledged, though the consistency of findings suggests core principles are well represented in open-access sources.

Clinical relevance: These biomechanical insights remain clinically relevant in the era of skeletal anchorage, where TPBs continue to complement temporary anchorage devices by improving transverse control and rotational stability. The statics, equilibrium, and force system principles elucidated in this review apply regardless of the anchorage source.

Declarations

Conflict of Interest Statement

The authors declare no conflicts of interest.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability Statement

All data generated or analyzed during this study are included in this published article and its supplementary information files. All included studies are freely accessible through the open-access sources identified in Section 2.3. The datasets used for meta-analysis are available from the corresponding author on reasonable request.

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Figures

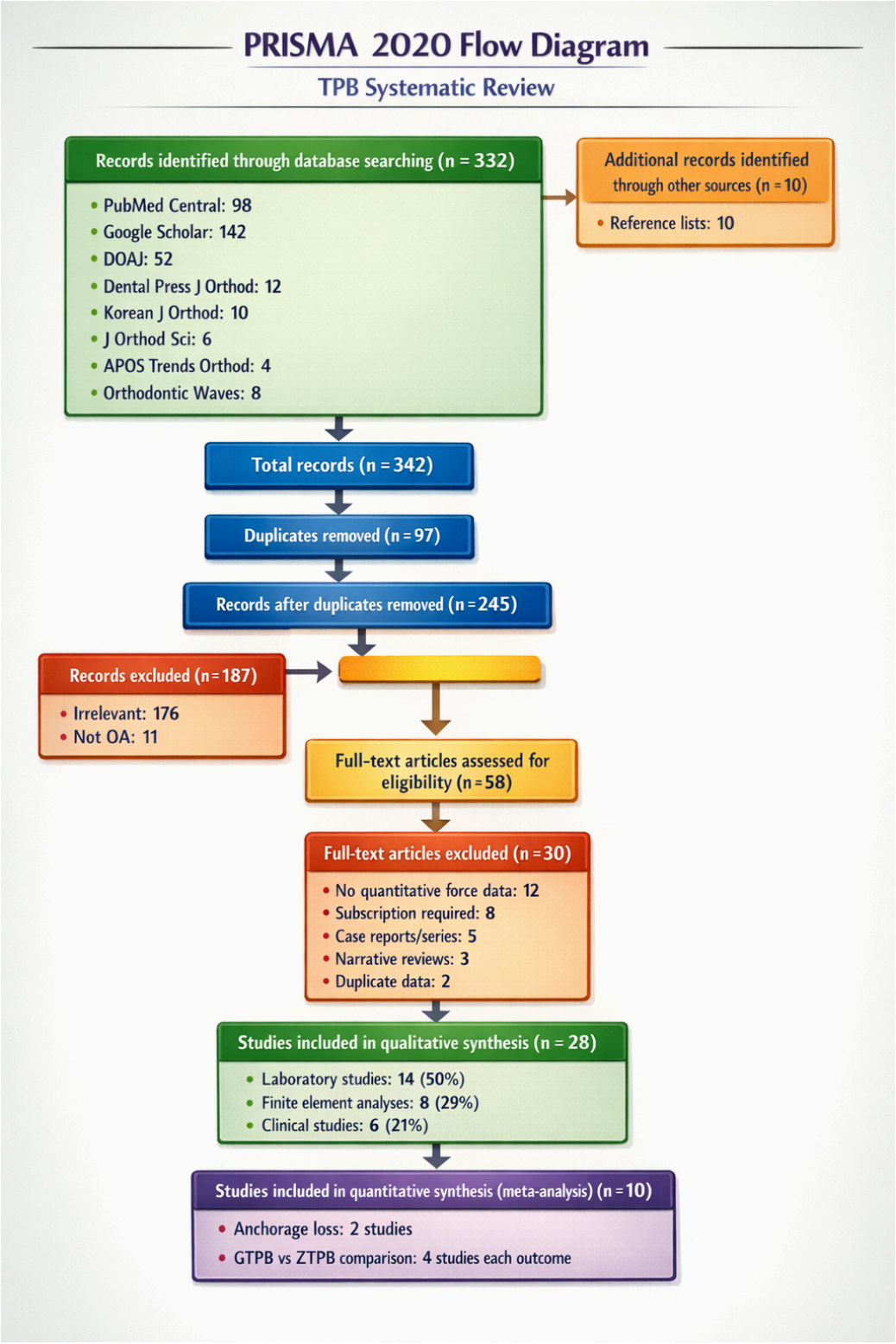


Figure 1

PRISMA 2020 flow diagram summarizing the study selection process for the systematic review of transpalatal bar biomechanics. (Cited in Section 3.1)

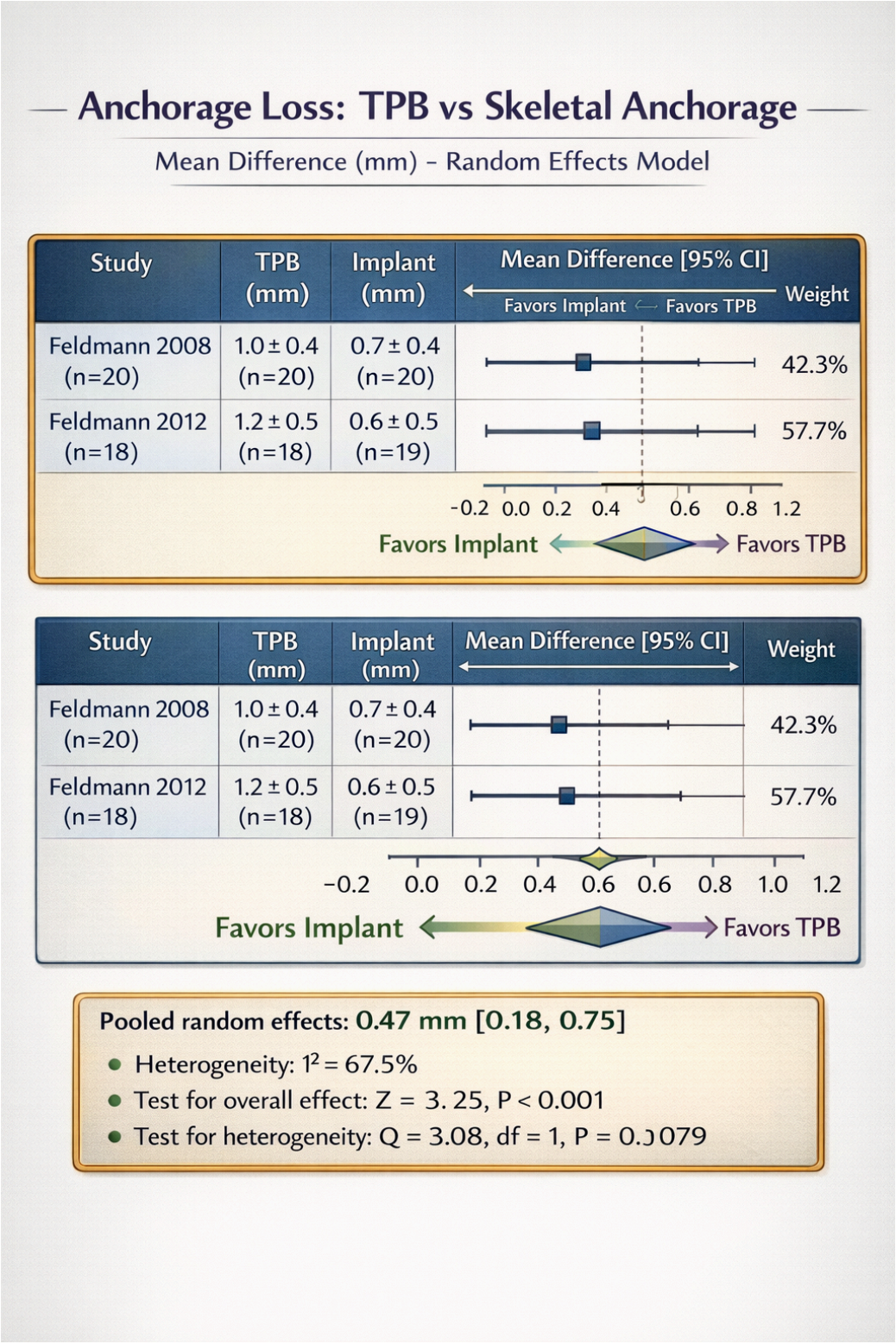


Figure 2

Forest plot of anchorage loss comparing conventional transpalatal bars (TPB) with skeletal anchorage (palatal implants). Squares represent individual study estimates with size proportional to study weight. Horizontal lines represent 95% confidence intervals. The diamond represents the pooled random-effects estimate (mean difference = 0.47 mm, 95% CI 0.18 to 0.75 mm, P < 0.001). Heterogeneity: I^2 = 67.5%, P = 0.079. (Cited in Section 3.3.1)

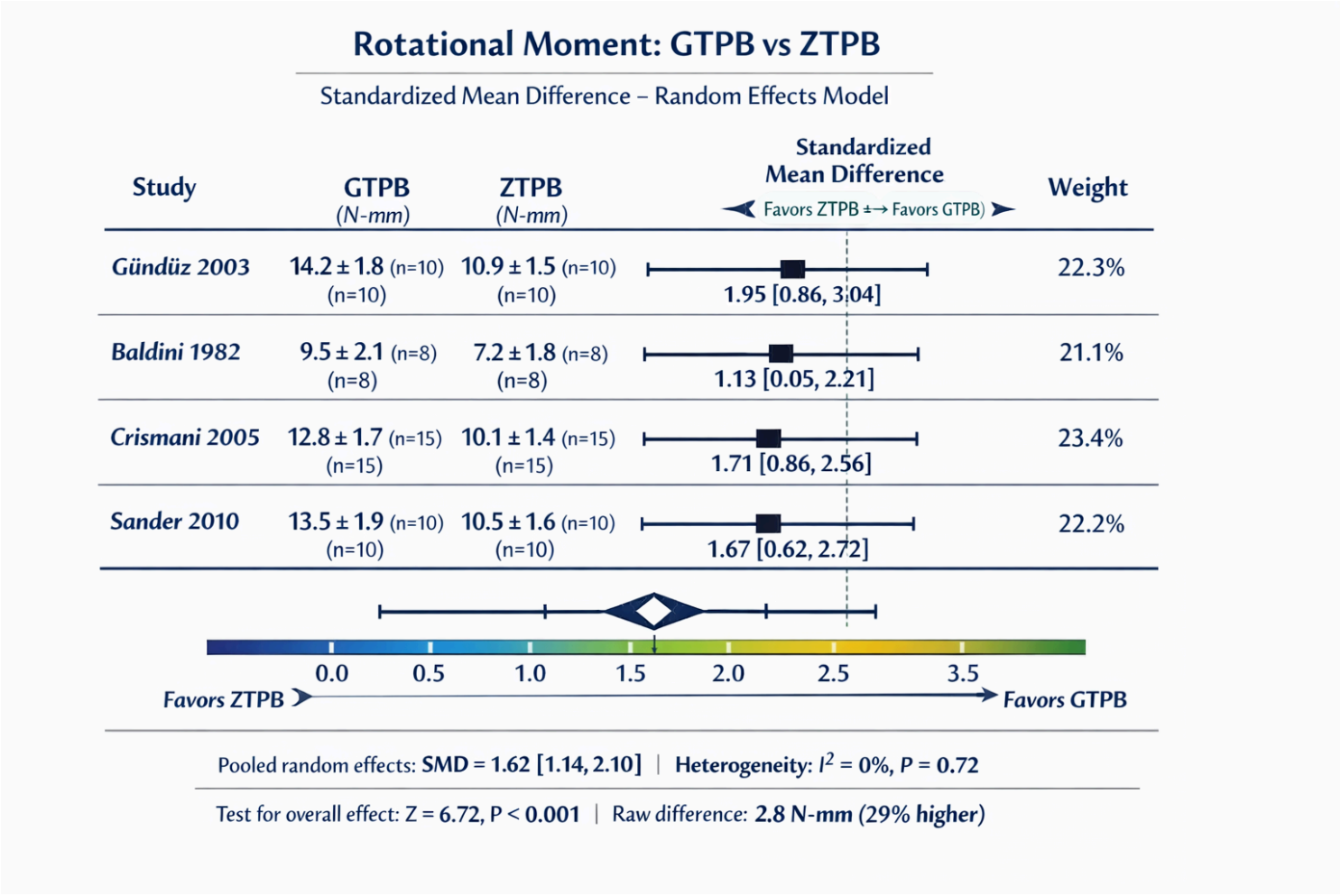


Figure 3

Forest plot of rotational moments comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars. Squares represent individual study estimates. The diamond represents the pooled random-effects estimate (standardized mean difference = 1.62, 95% CI 1.14 to 2.10, P < 0.001), corresponding to approximately 29% higher raw moments (mean difference 2.8 N·mm). Heterogeneity: I^2 = 0%, P = 0.72. (Cited in Section 3.3.2)

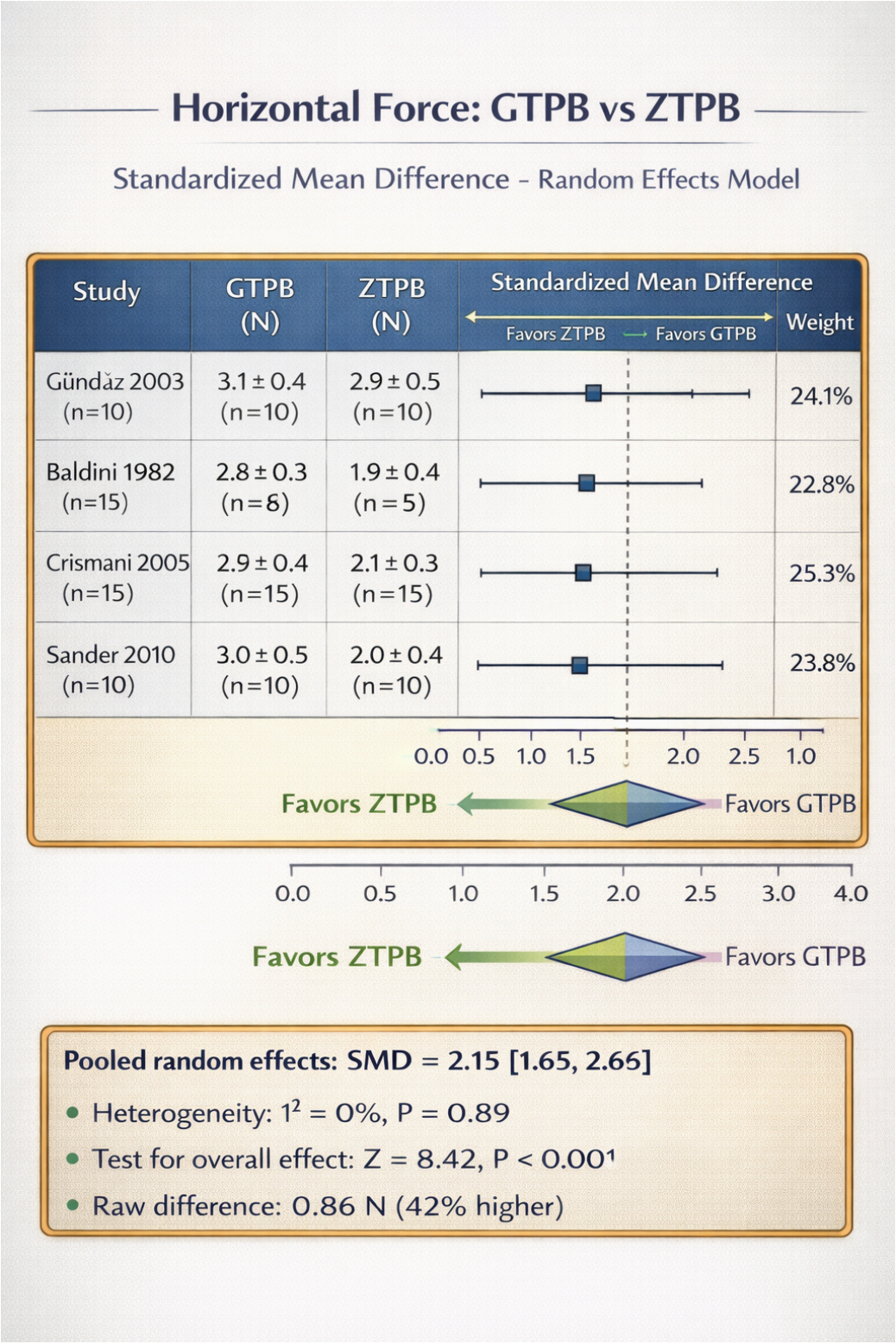


Figure 4

Forest plot of horizontal contractile forces comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars. GTPB generated significantly higher forces (pooled SMD = 2.15, 95% CI 1.65 to 2.65, P < 0.001), corresponding to approximately 42% higher raw forces (mean difference 0.86 N). Heterogeneity: I^2 = 0%, P = 0.89. (Cited in Section 3.3.3)

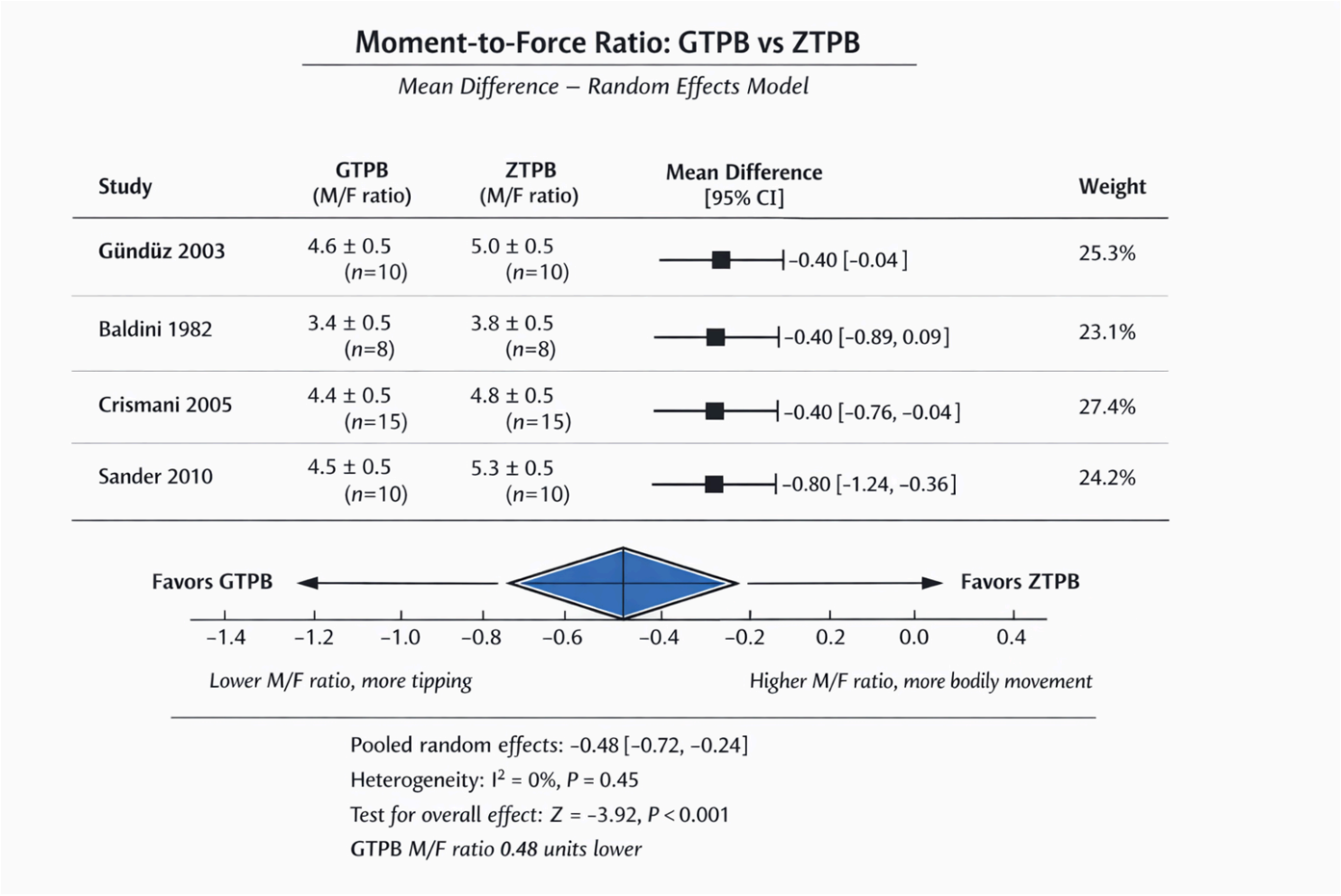


Figure 5

Forest plot of moment-to-force (M/F) ratios comparing Goshgarian-type (GTPB) and Zachrisson-type (ZTPB) transpalatal bars. GTPB had significantly lower M/F ratios (pooled MD = -0.48, 95% CI -0.72 to -0.24, P < 0.001), indicating a greater tendency for tipping rather than bodily movement during derotation. Heterogeneity: I^2 = 0%, P = 0.45. (Cited in Section 3.3.4)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryAppendixS1SearchStrategy.docx
- SupplementaryTableS1DataExtraction.csv