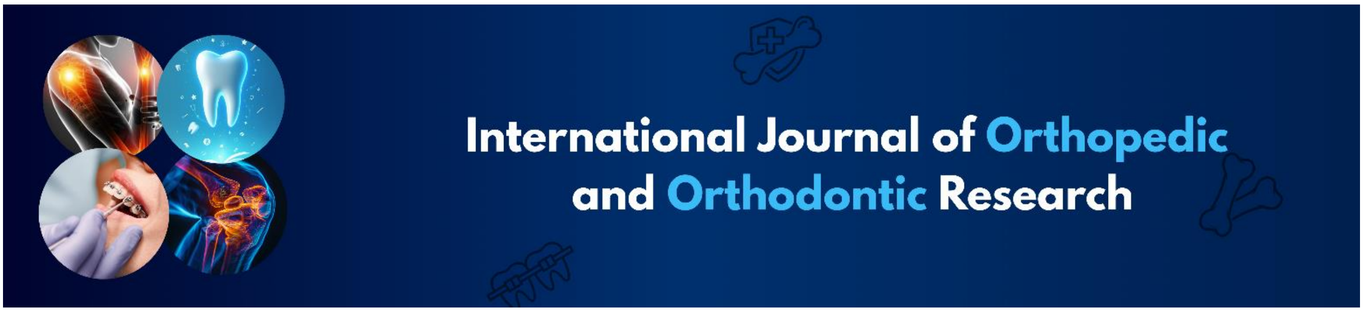

Advances in Skeletal Anchorage Systems: Clinical Outcomes in Orthodontic and Orthopedic Applications within Translational and Interdisciplinary Treatment Frameworks

Marco Antonio
Craniofacial Research Institute, Sapienza University of Rome, Rome, Italy

* Corresponding Author: **Marco Antonio**

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Abstract

Skeletal anchorage systems have fundamentally transformed contemporary orthodontic and orthopedic practice by providing stable, predictable anchorage that eliminates dependency on patient compliance and expands the boundaries of achievable tooth movement and growth modification. This review synthesizes current evidence on the clinical outcomes of temporary anchorage devices (TADs), mini-plates, and hybrid anchorage systems across orthodontic and orthopedic applications. The aim is to provide clinicians and researchers with a comprehensive framework for understanding the biomechanical principles, methodological approaches, and translational implications of skeletal anchorage in interdisciplinary patient care. Key biomechanical frameworks examined include load distribution dynamics, cortical bone engagement principles, and force-vector optimization strategies. Clinical applications are reviewed across major therapeutic domains including intrusion mechanics, en-masse retraction, open bite correction, Class II and Class III growth modification, maxillary protraction, mandibular control, and skeletal expansion. Comparative evaluation of clinical outcomes reveals that mini-implants achieve success rates exceeding 85-90% when appropriately placed and loaded, with factors including insertion site bone quality, operator experience, and patient factors significantly influencing stability. Mini-plates demonstrate superior stability for high-force orthopedic applications but require more invasive surgical placement. Hybrid systems combining skeletal anchorage with conventional appliances offer enhanced versatility for complex cases. Patient-reported outcomes indicate high acceptance levels despite the minimally invasive nature of placement procedures. Implementation considerations include surgical training requirements, cost-effectiveness analysis, and integration within multidisciplinary treatment planning. Challenges and future directions encompass digital workflow integration, 3D-guided placement, AI-assisted treatment planning, personalized anchorage strategies, and multicenter translational research frameworks. The review concludes that skeletal anchorage, when appropriately selected and implemented within evidence-based protocols, represents a paradigm shift enabling predictable, efficient, and minimally invasive correction of complex dentofacial problems.

Keywords: Skeletal Anchorage, Temporary Anchorage Devices, Orthodontic Biomechanics, Orthopedic Applications, Translational Orthodontics, Clinical Outcomes

1. Introduction

Anchorage control has historically represented one of the most challenging aspects of orthodontic and orthopedic treatment, determining the difference between successful tooth movement and undesirable reciprocal effects [1, 5]. Traditional anchorage strategies relied on intraoral structures—teeth, palate, alveolar bone—or extraoral devices requiring patient compliance, each with inherent limitations including reciprocal tooth movement, variable patient cooperation, and aesthetic concerns [1, 12].

The evolution of skeletal anchorage systems over the past three decades has fundamentally altered this landscape [1, 2, 12]. Temporary anchorage devices (TADs), including mini-implants and mini-plates, provide absolute anchorage by engaging cortical bone directly, eliminating the periodontal ligament-mediated damping that characterizes tooth-borne anchorage [1, 5]. This direct skeletal engagement enables application of orthodontic and orthopedic forces without unwanted tooth movement, expanding the scope of nonsurgical correction and improving treatment predictability [1, 2, 3].

The clinical and translational relevance of skeletal anchorage extends across multiple domains [1, 4, 11]. In orthodontics, TADs enable complex tooth movements—molar intrusion, en-masse retraction, asymmetric correction—that were previously difficult or impossible without surgical intervention [1, 5, 13]. In orthopedic applications, skeletal anchorage facilitates maxillary protraction, mandibular control, and skeletal expansion in patients beyond the optimal age for conventional growth modification [3, 7, 14]. The integration of skeletal anchorage into surgical-orthodontic treatment further enhances possibilities for multidisciplinary care [1, 4].

This article aims to provide a comprehensive review of advances in skeletal anchorage systems, focusing on clinical outcomes across orthodontic and orthopedic applications. The scope encompasses biomechanical foundations, classification of anchorage systems, clinical applications, comparative evaluation, implementation strategies, and emerging directions. By synthesizing current evidence within translational and interdisciplinary frameworks, this review seeks to equip practitioners with the knowledge necessary for evidence-based, patient-centered application of skeletal anchorage technologies.

2. Conceptual Frameworks and Methodological Approaches

2.1. Biomechanical Foundations of Skeletal Anchorage

The biomechanical superiority of skeletal anchorage derives from direct cortical bone engagement, which fundamentally alters force transmission compared to tooth-borne anchorage [1, 5, 6]. When orthodontic forces are applied to teeth, the periodontal ligament acts as a viscoelastic interface, damping force transmission and enabling tooth movement as a necessary consequence of anchorage [1, 5]. Skeletal anchorage eliminates this damping, enabling force application without reciprocal movement [1, 2].

Load distribution at the bone-implant interface determines TAD stability and clinical success [6, 8[9]. Primary stability, achieved immediately upon insertion, depends on mechanical interlock between implant threads and cortical bone [6, 8]. Factors influencing primary stability include cortical bone thickness, insertion torque, implant design (diameter, length, thread configuration), and placement technique [6, 8, 9]. Secondary stability develops over weeks to months through osseointegration, though the extent of bone-implant integration for orthodontic TADs remains less than for prosthetic implants due to the absence of functional loading [6, 9].

Force vector control represents a critical advantage of skeletal anchorage [1, 5, 13]. By selecting implant position and attachment geometry, clinicians can precisely direct force application to achieve desired tooth movement while minimizing unwanted components [1, 13]. The point of force application relative to the center of resistance of the target tooth or segment determines the moment-to-force ratio and resultant center of rotation, enabling controlled tipping, bodily movement, or intrusion as required [1, 5].

Cortical bone engagement principles guide implant site selection and placement technique [6, 8, 9]. Maximum stability is achieved when implants engage adequate cortical bone thickness—typically 1.5-2.0 mm—without penetrating critical structures including dental roots, neurovascular bundles, or maxillary sinus [6, 8, 9]. Interradicular sites between second premolar and first molar in both arches offer favorable bone quality with acceptable cortical thickness, while midpalatal and retromolar sites provide alternative locations for specific applications [6, 8].

2.2. Classification and Design of Skeletal Anchorage Systems

Skeletal anchorage systems encompass a diverse range of devices designed for specific clinical applications [1, 2, 3, 4]. Mini-implants, also termed temporary anchorage devices or miniscrews, represent the most widely used category, characterized by small diameter (1.2-2.0 mm) and lengths ranging from 6-12 mm [1, 2]. These devices are designed for relatively short-term use (months to 2-3 years) and are typically removed following treatment completion [1, 2]. Insertion is minimally invasive, often performed under local anesthesia without flap elevation [1, 2].

Mini-plates, in contrast, are larger devices requiring surgical placement with flap elevation and screw fixation to cortical bone [3, 4, 14]. Mini-plates offer superior stability for high-force applications—including orthopedic correction requiring forces exceeding 500 grams—and can withstand extended loading periods [3, 14]. The transmucosal attachment arm extends through soft tissue, enabling force application without implant penetration of the oral mucosa [3, 4]. Mini-plates are particularly valuable for orthopedic applications in growing patients and for skeletal anchorage in compromised bone sites [3. 14].

Hybrid anchorage systems combine skeletal anchorage with conventional orthodontic appliances to achieve treatment objectives impossible with either approach alone [2, 7, 10]. The hybrid Hyrax appliance, utilizing palatal TADs to support maxillary expansion, exemplifies this approach, enabling skeletal expansion in older adolescents and young adults where conventional tooth-borne expansion would produce primarily dental tipping [2, 7]. Modular systems incorporating multiple TADs enable complex force systems for comprehensive treatment objectives [2, 10].

Orthopedic anchorage applications represent a distinct category utilizing skeletal anchorage for growth modification rather than tooth movement [3, 7, 14]. Bone-anchored maxillary protraction (BAMP) employs mini-plates in the infrazygomatic crest of the maxilla and the anterior mandible to apply intermaxillary forces for Class III correction [3, 14]. Similar approaches utilize skeletal anchorage for mandibular advancement, vertical control, and asymmetric correction [3, 7].

2.3. Methodological Frameworks for Clinical Evaluation

Evidence-based assessment of skeletal anchorage outcomes requires methodologically rigorous evaluation frameworks [11, 12, 15]. Prospective clinical trials with defined inclusion criteria, standardized protocols, and appropriate outcome measures provide the highest quality evidence [11, 12]. Success rate evaluation typically defines success as implant survival without mobility or significant bone loss throughout the treatment period [1, 2, 11].

Comparative clinical trials examining different implant designs, placement protocols, and loading regimens inform evidence-based practice [11, 12, 15]. Meta-analyses synthesizing data across multiple studies provide quantitative estimates of success rates and identify factors influencing outcomes [11, 12]. Systematic reviews following PRISMA guidelines ensure transparent and comprehensive evidence synthesis [11, 12].

Stability assessment encompasses both clinical evaluation and imaging-based analysis [6, 8, 9]. Clinical assessment includes mobility testing, peri-implant soft tissue evaluation, and pain assessment [1, 6]. Imaging modalities including periapical radiography, cone-beam computed tomography, and micro-CT enable evaluation of bone-implant interface, peri-implant bone levels, and implant position relative to adjacent structures [6, 8, 9].

Patient-reported outcome measures (PROMs) provide essential perspectives on treatment experience and acceptance [15, 16]. Instruments assessing pain, functional impact, aesthetic concerns, and overall satisfaction during and after skeletal anchorage treatment enable patient-centered evaluation [15, 16]. Studies consistently report high acceptance levels despite transient discomfort during placement and adjustment [15, 16].

Table 1: Classification and Clinical Indications of Skeletal Anchorage Systems in Orthodontic and Orthopedic Applications

System Type	Design Characteristics	Anatomical Placement	Primary Indications	Age Considerations
Mini-implants (TADs)	Diameter 1.2-2.0 mm; Length 6-12 mm; Self-drilling or self-tapping thread designs	Interradicular sites (maxilla: between premolars/molars; mandible: similar); Midpalatal; Retromolar; Infrazygomatic crest	Orthodontic anchorage: intrusion, retraction, protraction, space closure, molar distalization, open bite correction	Adolescents to adults; caution in mixed dentition due to root proximity [1, 2, 5, 6]
Mini-plates	Titanium plates with transmucosal attachment arms; Secured with 2-4 monocortical screws	Zygomatic buttress; Anterior mandible; Infrazygomatic crest; Lateral nasal wall	High-force orthopedic applications; Maxillary protraction; Mandibular advancement; Skeletal expansion; Cases requiring >500g force	Growing patients for orthopedic correction; Any age with adequate bone [3, 4, 14]
Hybrid Hyrax	Palatal TADs (2-4) combined with expansion screw; Tooth-borne and bone-borne components	Palatal TADs in paramedian palate; Expansion screw attached to molars	Skeletal transverse deficiency in older adolescents/adults; Failed prior expansion; Asymmetric expansion needs	Adolescents (CVMS 4-6) and adults; Ideal for patients beyond conventional RME age [2, 7, 10]
Palatal Implants	Larger diameter (3-5 mm); Designed for longer-term stability	Midpalatal region posterior to incisive foramen	Absolute posterior anchorage; Molar distalization; Space closure; Orthopedic anchorage	Adults and older adolescents with adequate palatal bone [2, 8]
Infrazygomatic Crest TADs	Longer TADs (12-16 mm); Designed for engagement of zygomatic buttress	Infrazygomatic crest region at mucogingival junction	Posterior intrusion; Molar distalization; Asymmetric correction; High-pull headgear substitution	Adolescents and adults; Requires adequate bone thickness [5, 13
Mandibular Buccal Shelf TADs	Angled placement in dense cortical bone of buccal shelf	Mandibular buccal shelf between molars	Mandibular molar distalization; Protraction; Asymmetric correction	Adolescents and adults; Dense cortical bone provides excellent stability [5, 6]
Modular Skeletal Anchorage Systems	Multiple TADs integrated with custom appliances; Digital design and fabrication	Patient-specific placement guided by 3D planning	Complex multidisciplinary treatment; Combined skeletal and dental correction	Any age with appropriate bone; Ideal for complex cases [2, 10]

3. Applications and Clinical Case Frameworks

3.1. Orthodontic Applications

The versatility of skeletal anchorage enables orthodontic tooth movements that were previously difficult or impossible without surgical intervention or significant patient compliance [1, 5, 13]. Intrusion mechanics represent one of the most valuable applications, particularly for overerupted molars, anterior open bite correction, and deep bite management [1, 5, 13]. TADs placed in the infrazygomatic crest or buccal shelf enable controlled intrusion of posterior segments without the reciprocal extrusion that would occur with conventional mechanics [5, 13]. Anterior open bite secondary to posterior overeruption can be corrected through true intrusion, eliminating the need for surgical impaction in selected cases [5, 13].

En-masse retraction of anterior segments following premolar extraction exemplifies the efficiency of skeletal anchorage for space closure [1, 5]. Conventional mechanics relying on posterior teeth for anchorage inevitably produce some forward movement of the anchor unit, prolonging treatment and potentially compromising outcomes [1, 5]. TADs placed in the buccal shelf or infrazygomatic crest provide absolute anchorage, enabling complete space closure through anterior retraction without posterior movement [1, 5, 13]. Force vectors can be optimized by varying attachment height and position to achieve controlled tipping or bodily movement as required

[1, 13].

Open bite correction through posterior intrusion or anterior extrusion represents a mechanistically distinct application with skeletal anchorage [5, 13]. For open bites resulting from posterior vertical excess, TADs enable intrusion of maxillary molars, allowing mandibular autorotation and bite closure [5, 13]. This approach addresses the skeletal etiology directly rather than compensating through anterior extrusion, improving stability [5, 13]. For anterior open bites with significant incisor display, TADs can facilitate controlled incisor extrusion when indicated [5].

Asymmetry management benefits from the selective force application enabled by skeletal anchorage [1, 5, 13]. Unilateral TAD placement allows asymmetric force systems for correction of midline deviations, unilateral space closure, and differential molar movement [1, 5]. Cases requiring greater movement on one side can be managed with unilateral TAD anchorage while the contralateral side serves as the anchor unit, enabling efficient asymmetric correction [1, 13].

3.2. Orthopedic and Growth Modification Applications

Skeletal anchorage has expanded the possibilities for orthopedic correction in growing patients and enabled growth modification in patients beyond the optimal age for conventional appliances [3, 7, 14]. Bone-anchored maxillary protraction (BAMP) represents a paradigm shift in Class III management [3, 14]. By placing mini-plates in the infrazygomatic crest of the maxilla and the anterior mandible, intermaxillary elastics apply continuous forces for maxillary advancement and mandibular restraint [3[14]. This approach eliminates the dental side effects of tooth-borne protraction—maxillary incisor proclination and mandibular incisor retroclination—achieving true skeletal correction [3, 14]. Long-term studies demonstrate stability of BAMP outcomes and reduced need for orthognathic surgery [3, 14].

Mandibular control through skeletal anchorage enables both advancement and restraint depending on clinical requirements [3, 7]. For Class II correction, skeletal anchorage can facilitate mandibular advancement without the dental compensation characteristic of functional appliances [3, 7]. For Class III cases with mandibular prognathism, skeletal anchorage provides stable anchorage for forces restraining mandibular growth [3, 14]. Vertical control through skeletal anchorage enables management of hyperdivergent patterns by intruding posterior segments or providing anchorage for vertical pull headgear [3, 7].

Skeletal expansion through bone-borne or hybrid appliances has extended the age range for successful maxillary expansion [2, 7, 10]. Conventional rapid maxillary expansion relies on sutural opening in growing patients; after sutural fusion, tooth-borne expansion produces primarily dental tipping with minimal skeletal effect and significant risk of periodontal complications [2, 7]. Hybrid Hyrax and MARPE appliances utilizing palatal TADs distribute expansion forces directly to skeletal structures, enabling true sutural opening even in older adolescents and young adults [2, 7, 10]. CBCT studies confirm skeletal expansion with minimal dental tipping, improved stability, and reduced relapse [2, 10].

3.3. Surgical-Orthodontic Integration

The integration of skeletal anchorage with orthognathic surgery enhances possibilities for multidisciplinary treatment [1, 4, 11]. Pre-surgical orthodontic preparation in severe cases often requires significant tooth movement that challenges anchorage control; TADs provide stable anchorage for decompensation without reciprocal effects on adjacent teeth [1, 4. Cases requiring asymmetric extraction patterns or differential space closure benefit from the selective force application enabled by skeletal anchorage [1, 4].

Post-surgical stabilization represents another valuable application [1, 4]. Following orthognathic surgery, TADs can provide anchorage for elastics guiding occlusion into the planned relationship without the instability of tooth-borne forces [1, 4]. This approach enables controlled postsurgical tooth movement while skeletal structures heal in their new positions [1, 4].

Multidisciplinary planning integrating skeletal anchorage with surgical, periodontal, and prosthetic considerations requires systematic approaches [1, 4, 11]. Virtual surgical planning incorporating TAD placement enables comprehensive treatment simulation and identification of optimal implant positions relative to planned surgical movements [4, 10]. Collaboration between orthodontist and surgeon ensures appropriate implant selection, placement timing, and loading protocols [1, 4].

4. Comparative Evaluation and Implementation Strategies

4.1. Success Rates and Failure Factors

Skeletal anchorage success rates vary by device type, anatomical location, and patient factors, with systematic reviews reporting overall success rates of 85-90% for mini-implants [1, 2, 11, 12]. Factors associated with success include adequate cortical bone thickness, appropriate implant diameter and length, proper insertion technique, and avoidance of root proximity [1, 2, 6, 8]. Maxillary implants demonstrate slightly higher success rates than mandibular implants, attributed to favorable bone quality and reduced cortical thickness facilitating optimal insertion [1, 11, 12].

Failure occurs most commonly during initial healing or early loading, with late failures relatively uncommon [1, 2, 11]. Early failures typically result from inadequate primary stability, excessive insertion torque causing bone necrosis, or premature loading before soft tissue healing [1, 6, 8]. Root contact during insertion represents a preventable cause of failure, emphasizing the importance of appropriate imaging and placement technique [1, 2, 6]. Peri-implant inflammation and soft tissue hypertrophy can compromise stability and may necessitate implant removal [1, 2, 11].

Mini-plates demonstrate superior stability with success rates exceeding 95% in most series, reflecting the enhanced stability achieved through multiple screw fixation and favorable load distribution [3, 4, 14]. Plate exposure and soft tissue irritation represent the most common complications, typically manageable with local care [3,14]. Plate removal following treatment completion requires a second surgical procedure, a consideration in treatment planning [3,4].

4.2. Stability and Long-Term Outcomes

Long-term stability of orthodontic corrections achieved with skeletal anchorage compares favorably with conventional approaches [1, 5, 13]. The absolute anchorage provided by TADs enables complete space closure without anchor unit movement, improving occlusal outcomes and reducing the need for compensatory mechanics [1, 5, 13]. Intrusion mechanics achieve stable corrections of overerupted teeth when occlusal contacts are appropriately established and retention protocols observed [5, 13].

Skeletal changes achieved with bone-anchored orthopedic appliances demonstrate stability comparable to surgical correction in selected cases [3[14. BAMP studies with follow-up through completion of growth show maintained maxillary advancement and stable occlusal relationships, with few patients requiring subsequent orthognathic surgery [3[14. Skeletal expansion with hybrid appliances shows improved stability compared to tooth-borne expansion, attributed to true skeletal separation and reduced dental tipping [2, 7, 10].

4.3. Risk Assessment and Complication Management

Comprehensive risk assessment before skeletal anchorage placement includes evaluation of local anatomy, bone quality, medical history, and patient-specific factors [1, 2, 6, 8]. Imaging assessment—typically with CBCT for complex cases—identifies root proximity, cortical bone thickness, and anatomical variations that influence implant site selection [6, 8, 9]. Medical conditions affecting bone healing, including diabetes, osteoporosis, and medications influencing bone metabolism, warrant consideration [1, 2].

Complication management requires systematic approaches tailored to specific problems [1, 2, 11, 12]. Implant mobility detected at placement typically indicates inadequate primary stability; implant removal and replacement at an alternative site after healing is preferred to attempting salvage [1, 2]. Soft tissue complications including inflammation, hypertrophy, and coverage of implant heads respond to improved oral hygiene, soft tissue removal, or implant exposure as indicated [1, 11]. Root contact requires immediate implant removal and assessment of tooth vitality; timely removal minimizes risk of significant root damage [1, 2, 6].

4.4. Clinical Adoption Models and Cost-Effectiveness

Integration of skeletal anchorage into clinical practice requires systematic approaches to training, workflow, and patient communication [1, 15, 16]. Training in placement technique—including didactic instruction, simulated practice, and supervised clinical experience—develops the skills necessary for successful outcomes [1, 15]. Digital workflows incorporating 3D imaging and guided placement enhance accuracy and reduce complications, particularly for complex cases [10, 15].

Cost-effectiveness analysis of skeletal anchorage versus alternative treatments favors TADs when considering reduced treatment time, elimination of compliance requirements, and avoidance of more invasive procedures [15, 16]. For cases requiring orthognathic surgery in the absence of growth modification, the cost of TAD-supported orthopedic treatment compares favorably with surgical correction [15, 16]. Hybrid appliances, while more expensive than conventional approaches, may be cost-effective when they enable treatment that would otherwise require surgery [2, 10].

Healthcare system integration requires consideration of reimbursement models, regulatory requirements, and interdisciplinary coordination [1, 15]. Orthodontic training programs increasingly incorporate skeletal anchorage in curricula, ensuring that new practitioners enter practice with foundational knowledge [1, 15]. Continuing education opportunities enable established practitioners to develop skills as they integrate TADs into their practices [1, 15].

Table 2: Comparative Clinical Outcomes and Biomechanical Characteristics of Major Skeletal Anchorage Modalities

Modality	Success Rate (Range)	Force Capacity	Primary Treatment Applications	Typical Duration of Use	Interdisciplinary Compatibility
Mini-implants (TADs) - Interradicular	85-92% [1, 2, 11, 12]	50-300g continuous; up to 400g intermittent	Orthodontic anchorage: intrusion, retraction, space closure, molar distalization, open bite correction	6-24 months (removed after treatment)	High; compatible with all orthodontic mechanics; surgical placement optional [1, 5, 13]
Mini-implants (TADs) - Palatal	88-95% [2, 8, 11]	50-300g continuous	Posterior anchorage; Molar distalization; Asymmetric correction; Palatal expansion anchorage	6-24 months	High; excellent for multidisciplinary cases requiring posterior anchorage [2, 8]
Infrazygomatic Crest TADs	90-94% [5, 11, 13]	100-400g continuous; up to 500g intermittent	Posterior intrusion; En-masse retraction; Asymmetric correction; Molar distalization	12-30 months	High; requires careful placement to avoid sinus penetration [5, 13]
Mandibular Buccal Shelf TADs	92-96% [5, 6, 11]	100-400g continuous	Mandibular molar distalization; Protraction; Asymmetric correction; Class III mechanics	12-30 months	High; dense cortical bone provides excellent stability [5, 6]
Mini-plates	95-98% [3, 4, 14]	300-1000g continuous; orthopedic forces	Maxillary protraction (BAMP); Mandibular advancement; High-force orthopedic correction; Skeletal expansion	12-36 months (may remain through growth phase)	Requires surgical placement and removal; close orthodontic-surgical collaboration essential [3[14
Hybrid Hyrax/MARPE	90-95% [2, 7, 10]	Expansion forces (500-2000g during activation)	Skeletal transverse deficiency in older adolescents/adults; Failed prior expansion	Active expansion: 2-8 weeks; Retention: 3-6 months; Total: 6-12 months	Surgical placement of TADs; orthodontic activation; potential ENT collaboration for airway effects [2, 7, 10]
Palatal Implants	90-95% [2, 8]	50-300g continuous	Absolute posterior anchorage; Molar distalization; Space closure	12-36 months	Surgical placement required; compatible with complex mechanics [2, 8
Modular Skeletal Anchorage Systems	90-95% [2, 10]	Variable; customized to treatment needs	Complex multidisciplinary treatment; Combined skeletal and dental correction; Severe malocclusions	Varies with treatment complexity (12-36 months)	High; requires digital planning and interdisciplinary coordination [2, 10]

5. Challenges and Future Research Directions

5.1. Digital Workflow Integration

Digital technologies are transforming skeletal anchorage practice, from diagnosis through placement and loading [10, 15, 17]. Three-dimensional imaging with CBCT provides comprehensive assessment of bone quantity and quality, root proximity, and anatomical variations that influence implant site selection [10, 15]. Virtual implant placement enables simulation of optimal positions before clinical procedures, reducing complications and improving outcomes [10, 17].

Guided placement systems utilizing 3D-printed surgical guides translate digital plans to clinical reality with high accuracy [10, 17]. By constraining implant trajectory and depth, these systems minimize the risk of root contact and ensure optimal cortical engagement [10, 17]. Studies demonstrate significantly improved accuracy with guided versus freehand placement, particularly for less experienced operators [10, 17].

Digital workflows extending through treatment monitoring enable ongoing assessment of implant stability and force system performance [15, 17]. Intraoral scanning tracks tooth movement relative to implant position, enabling objective evaluation of treatment progress [15]. Remote monitoring technologies may eventually enable real-time force system adjustment based on treatment response [15, 17].

5.2. AI-Assisted Treatment Planning

Artificial intelligence applications in skeletal anchorage are in early stages but hold substantial promise [17, 18[19]. Machine learning algorithms trained on large datasets of clinical outcomes may eventually predict optimal implant selection, placement sites, and loading protocols for individual patients [17, 18. AI-assisted cephalometric analysis automates identification of anatomical landmarks and quantification of treatment changes, enhancing research efficiency [18[19].

Deep learning approaches to image analysis may improve detection of at-risk anatomical structures and automate implant trajectory planning [17, 19]. Neural networks trained on CBCT datasets can identify root proximity and cortical bone boundaries with accuracy approaching human experts [17, 19]. Integration of these tools into clinical workflows may reduce complications and improve outcomes, particularly for less experienced practitioners [17, 19].

5.3. Personalized Anchorage Strategies

The future of skeletal anchorage lies in personalization—matching device selection, placement, and loading to individual patient characteristics [1, 17, 20]. Patient-specific factors including bone density, cortical thickness, healing capacity, and treatment objectives influence optimal anchorage strategy [1, 17]. Genetic variation affecting bone metabolism and mechanotransduction may eventually inform implant selection and loading protocols [17, 20].

Biomechanical modeling incorporating patient-specific anatomy ensables prediction of implant performance under various loading conditions [1, 17]. Finite element analysis of bone-implant complexes identifies optimal implant designs and placement positions for individual patients [1, 17]. Validation of these models with clinical outcome data will enable iterative refinement and improved predictive accuracy [1, 17].

Personalized anchorage also requires attention to patient preferences, values, and circumstances [15, 16]. The best biomechanical solution is ineffective if unacceptable to the patient; shared decision-making incorporating patient perspectives on treatment burden, cost, and acceptable risk is essential for truly patient-centered care [15, 16].

5.4. Multicenter Translational Research Frameworks

Advancing the evidence base for skeletal anchorage requires collaborative research capable of generating adequately powered studies [1, 11, 15, 20]. Single-center studies, while valuable, are typically underpowered for subgroup analyses and may reflect local treatment patterns that limit generalizability [1, 11, 12]. Multicenter research networks enable pooling of patient data across diverse populations and treatment approaches, facilitating comparative effectiveness research and identification of optimal practices [1, 11, 15].

Standardized data collection protocols, including consistent outcome measures, imaging parameters, and follow-up schedules, are essential for meaningful data aggregation [1, 11, 15]. Registry-based research capturing real-world outcomes across diverse practice settings complements controlled trials by providing evidence on effectiveness in routine clinical practice [11, 15].

Translational research frameworks bridging basic science and clinical application are particularly important in skeletal anchorage, where understanding of bone-implant biology increasingly informs clinical practice [1, 17, 20]. Collaboration between materials scientists studying implant surfaces, biologists investigating osseointegration, and clinicians treating patients can accelerate translation of laboratory advances into therapeutic benefits [1, 17, 20].

Table 3: Advantages, Limitations, Risk Profiles, and Implementation Characteristics of Skeletal Anchorage Systems

System Type	Key Advantages	Limitations	Complication Risks	Surgical Requirements	Patient Compliance Dependency	Cost Considerations
Mini-implants (TADs)	Minimally invasive placement; Low cost; Wide range of applications; Removable without surgery; High patient acceptance	Limited force capacity (<400g continuous); Risk of root proximity; Variable stability in low-density bone; Limited lifespan (2-3 years max)	Root contact (3-8%); Implant mobility/failure (8-15%); Soft tissue inflammation; Peri-implantitis; Implant fracture during removal (rare)	Local anesthesia; Simple armamentarium; No flap elevation typically; 5-15 minutes per implant	Low; No compliance required for anchorage; Oral hygiene essential for soft tissue health	Low to moderate; Implant cost $50-200 each; Minimal additional armamentarium; Insurance coverage variable [1, 2, 5, 6, 11, 12]
Mini-plates	High force capacity (orthopedic forces); Excellent stability; Suitable for compromised bone; Long-term durability	Invasive placement and removal; Higher cost; Surgical facility required; Postoperative discomfort; Visible extraoral scars possible	Plate exposure (5-10%); Soft tissue irritation; Infection (2-5%); Screw loosening; Nerve injury (site-dependent); Hematoma	Flap elevation; Local or general anesthesia; Sterile surgical technique; 30-60 minutes; Second procedure for removal	Low; No compliance for anchorage; Postoperative care required; Oral hygiene maintenance essential	Moderate to high; Plate cost $300-600; Surgical facility fees; Anesthesia costs; Insurance may cover surgical component [3[4[14
Hybrid Hyrax/MARPE	Skeletal expansion in older patients; True sutural opening; Minimal dental tipping; Improved stability; Airway benefits	TAD placement required; Activation discomfort; Longer treatment than conventional RME; Learning curve for activation protocol	TAD failure (5-10%); Asymmetric expansion; Pain during activation; Ulceration; Relapse if overretention inadequate	TAD placement under local anesthesia; No flap typically; Guided placement recommended for accuracy	Low for TAD component; Activation compliance required (patient or parent); Retention compliance essential	Moderate; TADs ($100-400 total); Appliance fabrication ($300-600); Imaging costs; Cost-effective versus surgery [2, 7, 10]
Infrazygomatic Crest TADs	Accessible placement site; Excellent bone quality; Versatile force vectors; High success rates	Anatomical variation; Sinus proximity risk; Soft tissue management challenges; Limited interradicular space	Sinus penetration (2-5%); Soft tissue overgrowth; Placement failure; Root proximity (adjacent molars)	Local anesthesia; Simple armamentarium; May require flap in dense mucosa	Low; Oral hygiene access may be challenging; Requires patient cooperation for cleaning	Low to moderate; Similar to standard TADs [5, 11, 13
Palatal Implants	Excellent stability; Midpalatal bone quality; No root proximity concerns; Long-term retention possible	Surgical placement required; Palatal soft tissue management; Limited to posterior anchorage applications; Removal requires second procedure	Soft tissue overgrowth (common); Implant exposure loss; Failure to osseointegrate (5-10%); Discomfort during healing	Flap elevation; Local anesthesia; Sterile technique; 15-30 minutes	Low; Oral hygiene critical to prevent peri-implantitis	Moderate; Implant cost; Surgical fee; Second procedure for removal [2, 8
Modular Skeletal Anchorage Systems	Customized for complex cases; Optimized force systems; Digital precision; Versatile applications	High cost; Digital workflow required; Technical complexity; Limited long-term evidence	Device-specific; Dependent on implant types used; Software/planning errors possible	Varies with implant types; May include multiple sites; Guided placement typical	Low; Digital monitoring may enable remote tracking	High; Digital planning fees; Custom fabrication; Multiple implants; Complex case pricing [2, 10]

6. Conclusion

Skeletal anchorage systems have fundamentally transformed contemporary orthodontic and orthopedic practice, providing stable, predictable anchorage that eliminates dependency on patient compliance and expands the boundaries of achievable tooth movement and growth modification. This review has synthesized current evidence on the clinical outcomes of mini-implants, mini-plates, and hybrid systems across orthodontic and orthopedic applications, providing a comprehensive framework for understanding biomechanical principles, methodological approaches, and translational implications.

The fundamental insight emerging from this analysis is that skeletal anchorage, when appropriately selected and implemented within evidence-based protocols, enables treatment objectives that were previously difficult or impossible to achieve. Orthodontic applications including intrusion, en-masse retraction, open bite correction, and asymmetry management benefit from the absolute anchorage provided by TADs, eliminating reciprocal tooth movement and improving treatment efficiency [1, 5, 13]. Orthopedic applications including maxillary protraction, mandibular control, and skeletal expansion have been revolutionized by bone-anchored approaches that achieve true skeletal correction without the dental side effects characteristic of tooth-borne appliances [3, 7, 14].

Clinical implications of these findings are substantial. Appropriate case selection—matching anchorage system to treatment objectives, anatomical considerations, and patient characteristics—determines success [1, 2, 3, 4]. Technical expertise in implant placement and force system design must be developed through systematic training and maintained through continued learning [1, 15]. Interdisciplinary collaboration, particularly with surgical colleagues for plate placement and complex cases, enhances outcomes and expands treatment possibilities [1, 4, 11].

The contribution of this review to the field lies in its integration of biomechanical theory with clinical outcomes, providing a conceptual framework that bridges the gap between understanding of bone-implant biology and practical treatment decision-making. By organizing knowledge around clinical applications rather than specific devices, the review aims to equip practitioners with transferable understanding applicable to new technologies as they emerge.

Future research directions promise continued advancement in skeletal anchorage practice. Digital workflow integration, including 3D imaging, guided placement, and AI-assisted planning, will enhance precision and reduce complications [10, 15, 17, 19]. Personalized anchorage strategies informed by patient-specific factors and biomechanical modeling may optimize outcomes for individual patients [1, 17, 20]. Multicenter translational research frameworks will be essential for generating the evidence base needed to guide these emerging technologies [1, 11, 15, 20].

The ultimate goal of skeletal anchorage—predictable, efficient, minimally invasive correction of complex dentofacial problems—is increasingly achievable as understanding deepens and technologies advance. Grounded in sound biomechanical principles and enabled by emerging technologies, skeletal anchorage offers patients and clinicians a powerful tool for achieving optimal outcomes across the spectrum of orthodontic and orthopedic treatment needs.

7. References

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