



STABILITY OF ORTHODONTIC MINISCREWS UNDER CYCLIC LOADING: A BIOMECHANICAL REVIEW

Orthodontology

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ABSTRACT

Temporary anchorage devices have revolutionized orthodontic biomechanics by providing reliable skeletal anchorage for complex tooth movements. Among these, miniscrews have gained widespread popularity due to their simplicity, versatility, and minimal invasiveness. However, their stability remains a concern, particularly when subjected to cyclic orthodontic forces that mimic real intraoral conditions. Repeated functional loading may induce subtle displacement at the bone-implant interface, gradually compromising anchorage and leading to clinical failure. Understanding this displacement under cyclic loading provides valuable insight into the biomechanical thresholds that distinguish physiological adaptation from pathological loosening. This review explores the biomechanical principles governing miniscrew stability, with a focus on how cyclic forces influence their displacement patterns and long-term performance. By consolidating evidence from experimental and computational models, it highlights key factors such as insertion torque, bone quality, implant design, and loading magnitude. The synthesis aims to provide clinicians with a clearer understanding of how miniscrews behave under functional forces and how this knowledge can optimize their clinical application.

KEYWORDS

Orthodontic miniscrews; cyclic loading; displacement; biomechanical stability; anchorage

INTRODUCTION

Temporary anchorage devices, especially orthodontic miniscrews have transformed orthodontic biomechanics by providing compliance-independent skeletal anchorage for complex tooth movements [1]. Their success is well documented in short-term applications, but an important question extends beyond primary stability at placement: how do these devices behave when subjected to repeated functional (cyclic) loading? Such cyclic forces, generated by mastication, orthodontic activation, or elastics, can induce small displacements at the bone-implant interface and gradually reduce anchorage quality over time [2,3].

Clinical and preclinical studies have shown that miniscrews may undergo secondary displacement, or migration, under orthodontic forces, most often in the direction of the applied load [4,5]. Interestingly, this can occur even in devices that remain clinically "stable," suggesting that mobility does not always equate to failure but may represent a spectrum of adaptive bone-implant responses. From a biomechanical perspective, interfacial micromotion and the resulting strain fields can influence early bone healing and remodeling around screw threads. However, excessive interfacial strains may lead to fibrous encapsulation and subsequent loosening [6].

Key biomechanical factors influencing stress transfer and displacement under cyclic loading include insertion angle, bone quality, screw design, and applied force magnitude and direction. [7,8]. This review consolidates experimental, computational, and clinical insights to clarify thresholds between physiological adaptation and pathologic motion and to suggest strategies that can help preserve anchorage reliability in long-term orthodontic treatment.

BIOMECHANICAL BASIS OF MINISCREW STABILITY

The stability of orthodontic miniscrews depends on the balance between implant design, bone properties, and loading conditions. Finite element analyses have shown that stresses concentrate at the crestal cortical bone and the first few threads, especially under moment loading, highlighting this region as critical for long-term anchorage [9]. Screw head geometry also alters force transfer: different designs, such as mushroom or cross slots, distribute stress differently across the implant, which can influence displacement and deformation patterns [10].

Beyond head configuration, thread design, pitch, and implant taper

play vital roles in stress dissipation. Studies demonstrate that inappropriate geometry can intensify stress concentrations in cortical bone, whereas optimized design promotes more uniform load sharing and improved resistance to micromotion [11]. Insertion angle is another determinant; screws placed perpendicularly (90°) show reduced stress peaks compared with oblique insertions, making angle optimization essential for stability [12].

Material properties further modulate performance. Comparisons between titanium and alternative materials such as polyaryletheretherketone (PEEK) reveal that titanium maintains higher anchorage under cyclic forces, although insertion angle remains a decisive factor for both materials [13]. Collectively, these biomechanical insights emphasize that miniscrew stability is not determined by a single factor but by the interplay of implant design, material, insertion strategy, and loading environment.

MICROMOTION OF MINISCREWS UNDER CYCLIC LOADING

Orthodontic miniscrews, once inserted into alveolar bone, are not entirely static devices. When subjected to repetitive intraoral forces such as mastication, orthodontic elastics, and archwire activation, they undergo subtle displacements at the bone-implant interface, collectively termed micromotion. This micromotion is largely time-dependent and results from the viscoelastic nature of bone tissue combined with progressive fatigue-related stress accumulation. Unlike single-load application, cyclic loading repeatedly challenges the implant-bone interface, creating conditions where even low-magnitude forces can, over time, contribute to measurable displacement and eventual loss of stability [14].

Dynamic load simulations have highlighted this phenomenon, demonstrating that removal torque decreases significantly after tens of thousands of cycles, indicating that cyclic rather than static forces are primarily responsible for progressive anchorage loss [14]. This aligns with evidence from cadaveric and bench models, which reveal creep-like, time-dependent displacement under continuous loading. Importantly, these findings emphasize that even in the absence of overt failure, sustained small forces can generate gradual interfacial motion that undermines anchorage efficiency [15].

The nature of the loading mode further influences micromotion. Finite element comparisons of continuous versus intermittent mechanics

during canine retraction have shown that dynamic cyclic protocols generate higher crestal stress concentrations than static loads. This amplifies the potential for localized bone strain and displacement, particularly around the cortical crest where miniscrews derive much of their primary stability [16].

In addition to loading mode, determinants of micromotion include screw geometry, thread pitch, insertion angle, and material properties. Thread design influences how forces are transmitted and dissipated into cortical and trabecular bone, while mechanical parameters such as static and dynamic stiffness or energy dissipation govern how cyclic stresses are accommodated. When these determinants are suboptimal, micromotion can exceed physiological thresholds and progress toward clinical instability [17].

CLINICAL IMPLICATIONS

Understanding micromotion under cyclic loading helps clinicians anticipate when miniscrews can provide reliable anchorage and when failure risk is elevated. Stable miniscrews ensure predictable mechanics for en-masse retraction, intrusion, or complex multidirectional movements. Awareness of displacement thresholds guides selection of screw design, insertion angle, and placement site to minimize micromotion and enhance long-term success. Clinicians should also plan for possible secondary migration, adjusting biomechanics and force vectors accordingly [18].

LIMITATIONS

Evidence on miniscrew micromotion under cyclic loading is constrained by heterogeneous study designs, short follow-ups, and variable definitions of “success” versus “migration.” Reported adverse events—root contact, soft-tissue inflammation, mucosal overgrowth, screw fracture, and sinus/nasal floor perforation—underscore the need for standardized outcomes and longer prospective trials focused on displacement thresholds and long-term stability [19].

Future Directions

Future research should focus on defining micromotion thresholds that distinguish physiological adaptation from pathological loosening. Advances in 3D finite element modeling, coupled with in vivo validation, may help standardize protocols for screw design, insertion strategies, and loading regimens. Emerging materials with enhanced fatigue resistance and novel surface modifications could further improve performance, paving the way for safer and longer-lasting miniscrew anchorage [20].

CONCLUSION

Orthodontic miniscrews provide valuable skeletal anchorage, yet their long-term stability is challenged by micromotion under cyclic loading. Displacement depends on factors such as bone quality, screw design, insertion angle, and force application. Recognizing these determinants allows clinicians to optimize placement and minimize failure risk. By integrating biomechanical understanding with careful case selection, miniscrews can remain a predictable tool for modern orthodontic practice.

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