

ABSTRACT

Clear aligner therapy (CAT) has emerged as one of the most rapidly advancing treatment modalities in contemporary orthodontics, driven by the integration of digital workflows, advanced biomaterials, and computer-assisted treatment planning. Despite its widespread clinical adoption, the biomechanical mechanisms underlying aligner-based tooth movement, the predictability of treatment outcomes, and the influence of biological and manufacturing variables remain only partially understood.

This doctoral thesis provides a comprehensive and multidisciplinary investigation of CAT through an integrated framework combining computational modeling, in vitro experimentation, and clinical outcome analysis. The primary aim was to evaluate the biomechanical behavior, clinical predictability, and biological implications of orthodontic treatment performed with clear aligners, while also assessing the impact of auxiliary systems and manufacturing protocols on force delivery and treatment accuracy.

Finite element analysis (FEA) was employed to simulate the biomechanical response of the dentoalveolar complex during upper molar distalization, revealing complex force systems and side effects, including the so-called “reversed bow effect”, characterized by unintended anterior proclination and incisor intrusion. These findings highlight the importance of optimized attachment design—particularly vertical rectangular attachments—and the integration of auxiliary systems to improve root control and movement efficiency.

To complement computational findings with experimental data, an in vitro study on Class II intermaxillary elastics evaluated force delivery under clinically relevant conditions. Mean inter-arch distances were quantified (e.g., 24.64 ± 2.10 mm between upper canine and lower first molar), demonstrating that the forces delivered by elastics significantly differ from manufacturers’ nominal values and undergo rapid decay in simulated oral environments. Among the tested configurations, 3/16" 4.5 oz elastics showed the most reliable force delivery and stability over time, emphasizing the importance of selecting auxiliaries based on real clinical distances rather than nominal specifications.

Clinical investigations focused on the predictability of orthodontic tooth movements achieved with aligners. Quantitative analysis through three-dimensional digital model superimposition revealed a consistent discrepancy between planned and achieved outcomes, particularly for rotational movements of teeth with rounded crown morphology. In some cases, only approximately 40% of the prescribed rotational movement was clinically expressed. Treatment design variables, including attachment configuration, staging protocols, and aligner replacement intervals, were found to significantly influence treatment accuracy.

The role of operator experience was also evaluated, demonstrating that clinician expertise is a critical determinant of treatment success. Experienced orthodontists achieved significantly higher predictability, particularly in complex movements, compared to less experienced operators. These findings underscore the importance of both biomechanical knowledge and digital workflow proficiency in aligner-based therapy.

From a biological perspective, the thesis investigated periodontal outcomes in patients with severe periodontitis treated with clear aligners. The results indicated that, when appropriate clinical protocols are followed, CAT can be safely applied in periodontally compromised patients, maintaining stable periodontal parameters while achieving orthodontic objectives. Additionally,

computational simulations suggested that reduced staging protocols (e.g., 0.1 mm per aligner in cases of reduced bone support) are necessary to maintain stress levels within physiological limits.

Finally, the thesis explored the role of manufacturing accuracy in aligner performance. An in vitro investigation of directly 3D-printed aligners demonstrated that post-processing protocols critically influence geometric fidelity. Aligners cured with printing supports intact exhibited significantly higher accuracy (mean RMS ≈ 0.119 mm) compared to those subjected to premature support removal (RMS ≈ 0.138 mm), with deviations up to approximately 250 μm . These findings indicate that discrepancies between planned and achieved tooth movements may also originate from manufacturing-related inaccuracies, in addition to biomechanical and biological factors.

Overall, the results of this doctoral research demonstrate that the effectiveness and predictability of clear aligner therapy are inherently multifactorial. Successful treatment requires a synergistic integration of accurate biomechanical planning, appropriate use of auxiliary systems, clinician expertise, controlled biological response, and standardized manufacturing workflows. Future advancements in artificial intelligence, digital orthodontics, and biomaterial science are expected to further enhance the precision and clinical performance of aligner-based orthodontic treatment.