


RESEARCH ARTICLE OPEN ACCESS

In Vitro Comparison of the Effectiveness of Different Attachment Shapes and Locations on Extrusion of the Upper Left Lateral Incisor Using Thermoplastic Aligners

Alexandra Bojrab¹ | Amin Akbari² | Dustin Broyles³ | Janine Magura¹ | Megann Lear¹ | George Eckert⁴ | Jie Chen² | Hakan Turkkahraman¹  | R. Scott Conley¹ 

¹Department of Orthodontics and Oral Facial Genetics, Indiana University School of Dentistry, Indianapolis, Indiana, USA | ²Department of Energy Engineering, Purdue University, Indianapolis, Indiana, USA | ³Indiana University School of Dentistry, Indianapolis, Indiana, USA | ⁴Department of Biostatistics and Health Data Science, Indiana University School of Medicine, Indianapolis, Indiana, USA

Correspondence: R. Scott Conley (scotconl@iu.edu) | Hakan Turkkahraman (haturk@iu.edu)

Received: 5 August 2024 | **Revised:** 27 November 2024 | **Accepted:** 12 December 2024

Funding: The authors received no specific funding for this work.

Keywords: attachments | clear aligners | orthodontic biomechanics

ABSTRACT

Objectives: The aim of this study was to compare the effectiveness of different attachment shapes and locations on the extrusion of the upper left lateral incisor (UL2) using thermoplastic aligners.

Materials and Methods: Seven typodonts were digitally printed with hemi-ellipsoid or rectangular attachments in the incisal, middle or cervical third of the UL2. Five clear aligners were fabricated for each typodont; each was tested twice. Forces and moments were measured with an orthodontic force tester during 0.2 mm simulated extrusion of the UL2. Analysis of variance (ANOVA) was used to determine the effects of group, tooth, and the group-by-tooth interaction on the outcomes. A two-sided 5% significance level was used for all tests.

Results: Altering attachment shape and location had a statistically significant effect on the forces and moments generated in each trial ($p < 0.01$), except for rectangular incisal and hemi-ellipsoid cervical ($p > 0.05$). The rectangular middle attachment generated the highest extrusive force ($F_z = 7.498$ N), followed by hemi-ellipsoid cervical ($F_z = 6.338$ N) and rectangular incisal ($F_z = 5.948$ N).

Conclusions: Varying direct attachment shape and location on the UL2 during extrusion has a significant effect on the forces and moments generated by thermoplastic aligners. The rectangular attachment located in the middle third generated the most effective extrusive force and least unwanted moment. For anchorage teeth, hemi-ellipsoid attachments located in the cervical third were found to be the most effective in minimising the reciprocal intrusive forces and unwanted moments.

1 | Introduction

The use of clear aligner therapy (CAT) has been a growing area of clinical care within the field of orthodontics for patients who are hesitant to wear metal brackets for cosmetic reasons. CAT was first made commercially available following FDA approval in 1998 [1]; however, removable aligner therapy began far earlier

with the introduction of the Tooth Positioner in 1946 [2] as a way to refine the final stages of orthodontic treatment [3]. As technology developed, the ability to use CAT for more severe malocclusions became possible [4, 5]. Since its inception in 1946, eight different generations of aligners have been developed, and currently, aligners can be designed and fabricated using advanced material and digital designs with the goal of efficiently

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2024 The Author(s). *Orthodontics & Craniofacial Research* published by John Wiley & Sons Ltd.

correcting all types of malocclusions [4, 5]. The proposed benefits of CAT are not only their cosmetic improvement, but also the enhanced comfort compared to traditional braces [3, 6]. CAT has also been found to be advantageous by improving patients oral hygiene.

Since their widespread launch in 1997, CAT has gained tremendous popularity and now constitutes a multi-billion-dollar segment of dental care expenditures. However, this unprecedented rise in popularity has not been accompanied by a corresponding improvement in the quality of evidence supporting the effectiveness of aligners. A recent scoping review revealed that the majority of published studies on clear aligner therapy (CAT) are at the lowest levels of evidence, including case reports, case series, narrative reviews and expert opinions [7]. The attempt to apply CAT to more complex malocclusion created a need for biomechanical improvement to effectively treat patients. However, current data indicate that the effectiveness of clear aligner therapy (CAT) remains uncertain and requires improvement [8, 9]. For instance, Kravitz et al. [10] found that 17.2% of patients (approximately one in six) switched from Invisalign to braces to complete their treatment. Based on their findings, they recommended setting realistic expectations, acknowledging that braces may be necessary to achieve optimal treatment outcomes. Kravitz et al. [11] performed the first prospective clinical study where they found the mean accuracy to be 41% for all movements. Among the notable findings, one of the least predictable movements was orthodontic extrusion which showed only 29.6% accuracy with the maxillary incisors being the most difficult. In a subsequent study [12], the extrusion accuracy was still clinically unpredictable with only 56% of the predicted movement occurring clinically demonstrating the need for further improvement. Studies indicate challenges in achieving extrusive movements, particularly from a cervical direction, with CAT. Proprietary owned industrial research claims that 2.5 mm of extrusion can be achieved on anterior teeth; however, little publicly available clinical data are available to support this claim [13].

Direct attachment designs in CAT have significantly evolved over time, driven by the need for precise and predictable tooth movements [4, 14]. Initially, attachments were primarily rectangular or ellipsoidal, serving as basic anchors to enhance aligner grip. Advances in biomechanics and digital orthodontics have led to the development of attachment designs tailored for specific movements such as rotation, extrusion and torque control. Innovations now include optimised attachments, featuring customised shapes and placements determined by digital simulations to maximise force efficiency while minimising patient discomfort [15–20]. Research highlights varying efficiencies of attachment designs such as horizontal rectangular, ellipsoid and semicircular attachments in different experimental setups [14, 21–23]. Limitations include inconsistent clinical data and neglect of attachment size and placement variability [24–26]. The need for further studies to determine optimal attachment design, size and location for predictable tooth movements, especially in extrusion, is emphasised. Therefore, the aim of this study was to compare the effectiveness of different attachment shapes and locations on the extrusion of the upper left lateral incisor using thermoplastic aligners. The null hypothesis to be

tested was that there is no difference in the effectiveness of different attachment shapes and locations on the extrusion of the upper left lateral incisor using thermoplastic aligners.

2 | Materials and Methods

In this *in vitro* study, extrusion of the upper left lateral incisor (UL2) was simulated using a standardised maxillary baseline (T0) model. A typodont was scanned, the teeth were segmented using MIMICS (version 25.0; Materialise, Belgium), and 3D printed using a Form 3B printer (Formlabs Inc., Somerville, Mass). Using the same dentofrom, six test groups were constructed with varying attachment design and location (Figure S1). A control model was constructed that was free of attachments. Three horizontal rectangular-shaped attachment groups were fabricated with the attachment located in either the incisal, middle or cervical third. Three gingivally straight hemi-ellipsoid shaped attachment groups were created with the attachment located in either the incisal, middle or cervical third. The size of the rectangular attachment was 3 mm wide, 1 mm height and 1 mm thick in a buccal lingual direction. The hemi-ellipsoid attachment was 3 mm wide, 2 mm height at the peak and 1 mm thick in the buccal lingual direction. Thermoplastic aligners for each typodont were formed according to the manufacturer's specifications using a Biostar thermoforming machine (Scheu Dental, Iserlohn, Germany) and a 0.75 mm thick aligner material (Great Lakes Dental Technologies, Tonawanda, NY). Five aligners were fabricated for each model with each aligner tested twice creating a total of 10 trials for each model configuration.

An orthodontic force tester (OFT) was used to measure the three-dimensional (3D) forces and moments delivered to not only the targeted UL2, but also the adjacent upper left central incisor (UL1) and canine (UL3) anchorage teeth. The accuracy of the OFT system and load conversion method was experimentally validated. A known force and moment were applied to a tooth's Local Coordinate System (LCS) by exerting a force at a specified distance from the origin of the LCS. The load components within the load cell's coordinate system were measured by the load cell, and these measured components were then transformed to the tooth's LCS using a specialised transformation programme. This experiment was conducted ten times with varying loads to ensure consistency and reliability. The measured moments and forces were compared against the known applied values to assess accuracy. The results demonstrated an average error of approximately 5% for moments and 1% for forces, which is deemed acceptable for this type of application.

For testing, the same T0 model was employed; however, to simulate tooth movement and enable the aligner to exert the desired extrusive force, the target tooth and its attachment were digitally moved 0.2 mm gingivally. This approach mimics the clinical scenario in which an aligner designed for the initial tooth position (T0) applies forces to move the tooth to the next planned position (T1). This experimental setup allowed us to assess how various attachment configurations influenced the extrusive forces generated by the aligners. Three Nano 17 load cells (ATI

Industrial Automation, Apex, NC) capable of measuring forces and moments in 3D were placed underneath the UL2, as well as UL1 and UL3. The load cells were stationary. Each tooth was connected to its corresponding load cell through an adaptor. After the segmented teeth were assembled in their dentofrom positions, the load cells were zeroed to set up the baseline. Then, the aligners were seated using an anteroposterior path of insertion by a single investigator for each trial. Readings were recorded for 10s after insertion, and the last 5s were averaged to try to minimise error from initial placement. Each aligner was tested twice.

All the load cells were calibrated prior to every test. Each load cell simultaneously measured the forces and moments in 3D (Fx, Fy, Fz, Mx, My and Mz). The load cell readings were transformed to a local coordinate system on the associated tooth with the origin at the middle of the incisal edge of the tooth. The X axis represented the mesial/distal direction; the Y axis was the buccal/lingual direction; and the Z axis was the occlusal/apical direction (Figure 1). In this study, the targeted parameters are forces in occlusal/apical direction (Fz), with (+) representing extrusion and (–) representing intrusion, and moments in buccal/lingual direction (Mx) with (+) representing buccal crown torque and (–) representing lingual crown torque.

2.1 | Statistical Analysis

With a sample size of five samples per attachment shape and location combination, the study has an 80% power to detect the differences between groups shown in the Table S1. Descriptive statistics of the forces and moments for each of the attachment shape and location combinations are given in Table S2. The effects of the attachment shape and location on the forces and moments were analysed using Analysis of variance (ANOVA) separately for each outcome. Pair-wise post hoc comparisons using Fisher's Protected Least Significant Differences were given in Table S3. A two-sided 5% significance level was used for all tests. Calculations were based on a two-sided 5% significance level, two-sample *t*-test and standard deviations shown in the table, estimated from a similar study by Wang et al. [27].

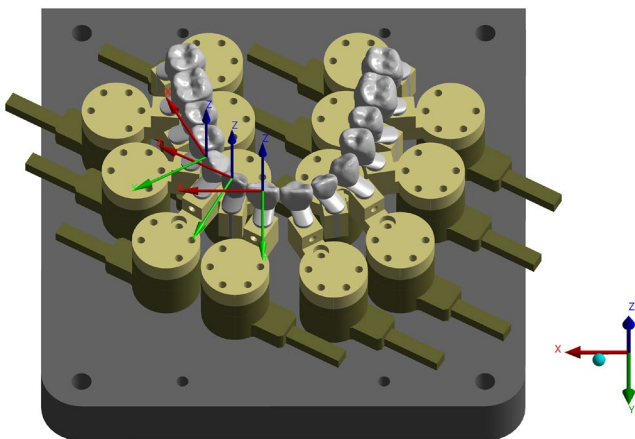


FIGURE 1 | The X, Y, Z coordinate system used for force and moment data collection.

3 | Results

Descriptive statistics of the Fz and Mx are given by boxplots for the UL2 (Figure 2), the adjacent UL1 (Figure 3) and the UL3 (Figure 4). When comparing the various attachment designs and locations for UL2, all Fz and Mx differences between groups were found to be statistically significant ($p < 0.01$) except the differences between the rectangular incisal and the hemi-ellipsoid cervical groups ($p = 0.26$ Fz, $p = 0.27$ Mx) and between the rectangular middle and hemi-ellipsoid middle groups for Mx ($p = 0.70$). Similarly, for UL3, most groups were statistically significant ($p < 0.05$) with exceptions for Fz rectangular cervical vs. hemi-ellipsoid middle ($p = 0.91$) and rectangular incisal vs. Control ($p = 0.93$) and for Mx no differences among rectangular cervical, hemi-ellipsoid cervical and Control ($p > 0.77$). For UL1 Fz, there were no differences among Control, hemi-ellipsoid middle and hemi-ellipsoid cervical ($p > 0.70$), between rectangular middle and hemi-ellipsoid middle ($p = 0.051$), or between rectangular middle and rectangular incisal ($p = 0.31$), with all other groups significantly different ($p < 0.05$). UL1 Mx had the fewest differences among groups, with rectangular cervical and hemi-ellipsoid incisal significantly different ($p < 0.05$) from Control, rectangular middle, rectangular incisal, hemi-ellipsoid middle and hemi-ellipsoid cervical, with no other significant differences among groups ($p > 0.05$). Fz ranged from -5.17 to 8.96 N on the targeted UL2 with the different attachment designs. Each attachment design yielded extrusion of the UL2 except for the hemi-ellipsoid design which caused an intrusive force. The Fz on the anchoring UL1 ranged from -7.66 to 2.39 N and -3.86 to -0.54 N for the anchoring UL3. Neither anchor tooth had attachments during testing. Mx on the targeted UL2 ranged from -70.47 to 77.74 N-mm, while ranged from -24.33 to 7.08 N-mm for the UL1, and -10.61 to 22.35 N-mm for the UL3.

4 | Discussion

Regardless of whether a clinician uses traditional orthodontic brackets or clear aligners, the forces applied to the teeth must obey Newton's laws. When extrusive or intrusive forces are applied labial to the centre of resistance of the tooth, a moment of force is created. The resulting moment may be considered favourable or unfavourable depending on the 3D goals for the clinical situation.

Despite the valuable information published to date, a common finding is 'more studies are needed' to confidently select proper attachments, sizes and locations to predict different bodily movements, especially extrusion [24–26, 28, 29]. This proposed investigation is novel because of the designs and locations of attachments being variable and studied. The tooth type is also varied in now using a maxillary lateral incisor rather than a maxillary central incisor. The project used three load cells allowing for not only direct measurement of the lateral incisor, but also the effects of the extrusion on the neighbouring teeth. Looking at the different attachment designs that have been shown as effective in extrusion, both horizontal rectangular and ellipsoid/semicircular designs were used to further what is already known about extrusion. These attachment shapes were specifically selected based on their distinct biomechanical advantages in facilitating extrusion

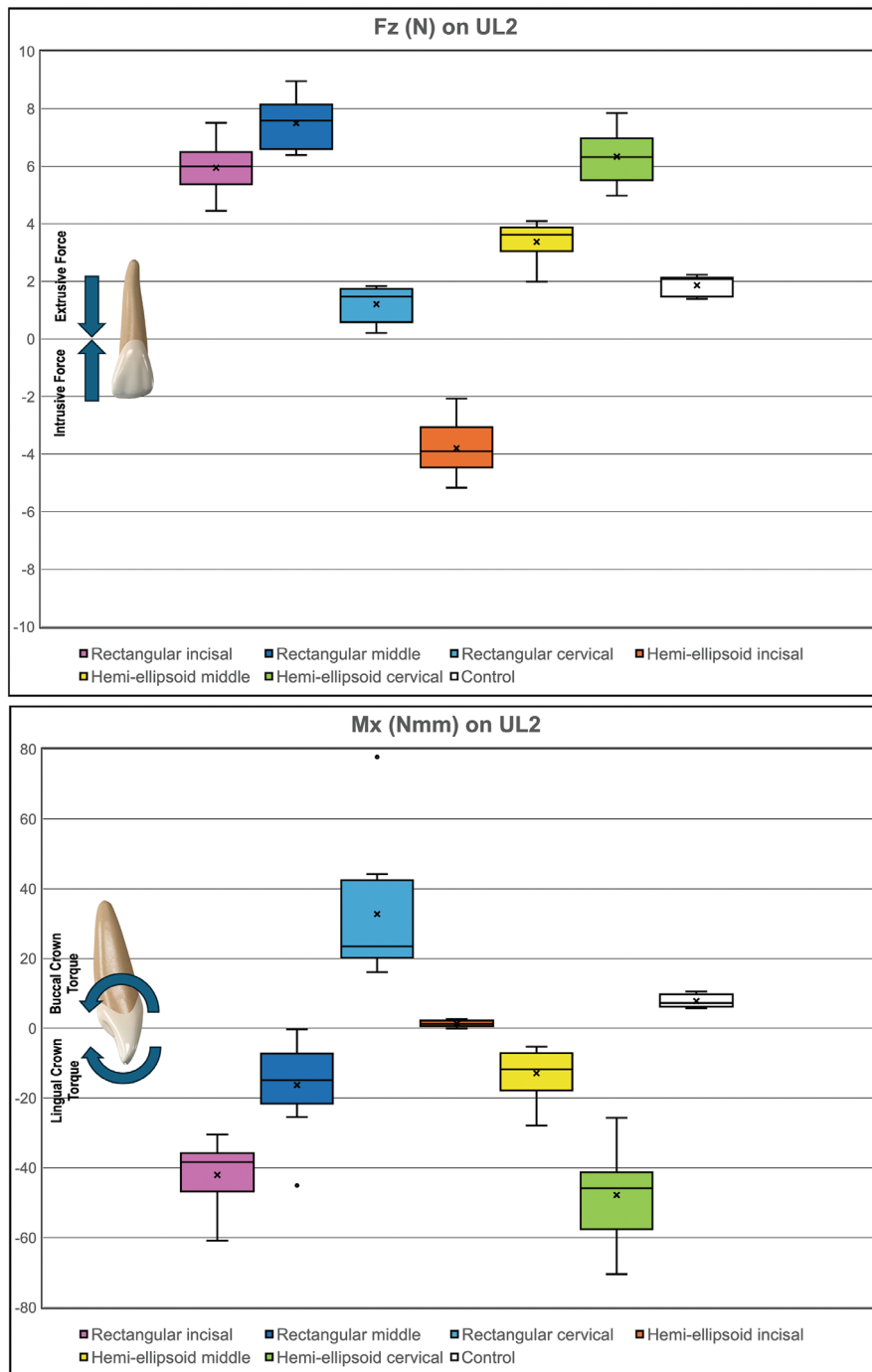


FIGURE 2 | Box and whisker plot depicting the distribution of the extrusive/intrusive forces (Fz) and bucco-lingual tipping moment (Mx) for the extruded upper left lateral incisor (UL2).

movements. Hemi-ellipsoid attachments are designed to provide a more focused force application while minimising patient discomfort, whereas rectangular attachments are known for their superior retention and control over complex movements due to their larger surface area for force transmission. Measuring the extrusive force of these designs on different locations of the lateral incisor will allow a better understanding of where to place the design to maximise the extrusive force with the most predictability. The aim of this study is to further evaluate the effects of direct attachments' shape and location on the forces and moments generated by thermoplastic aligners during extrusion.

Within the present study, the rectangular middle attachment and the hemi-ellipsoid cervical yielded the most effective extrusive force, while the rectangular cervical attachment displayed the least. Interestingly, hemi-ellipsoid attachment located in the incisal third revealed intrusive forces. With respect to proclination or retroclination moments, the rectangular attachment located in the middle third demonstrated the most limited (closest to zero) bucco-lingual moment. For the hemi-ellipsoid attachment groups, the middle and incisal locations showed the most limited (closest to zero) unwanted bucco-lingual moment. When both forces and moments were evaluated, the rectangular attachment in the middle third

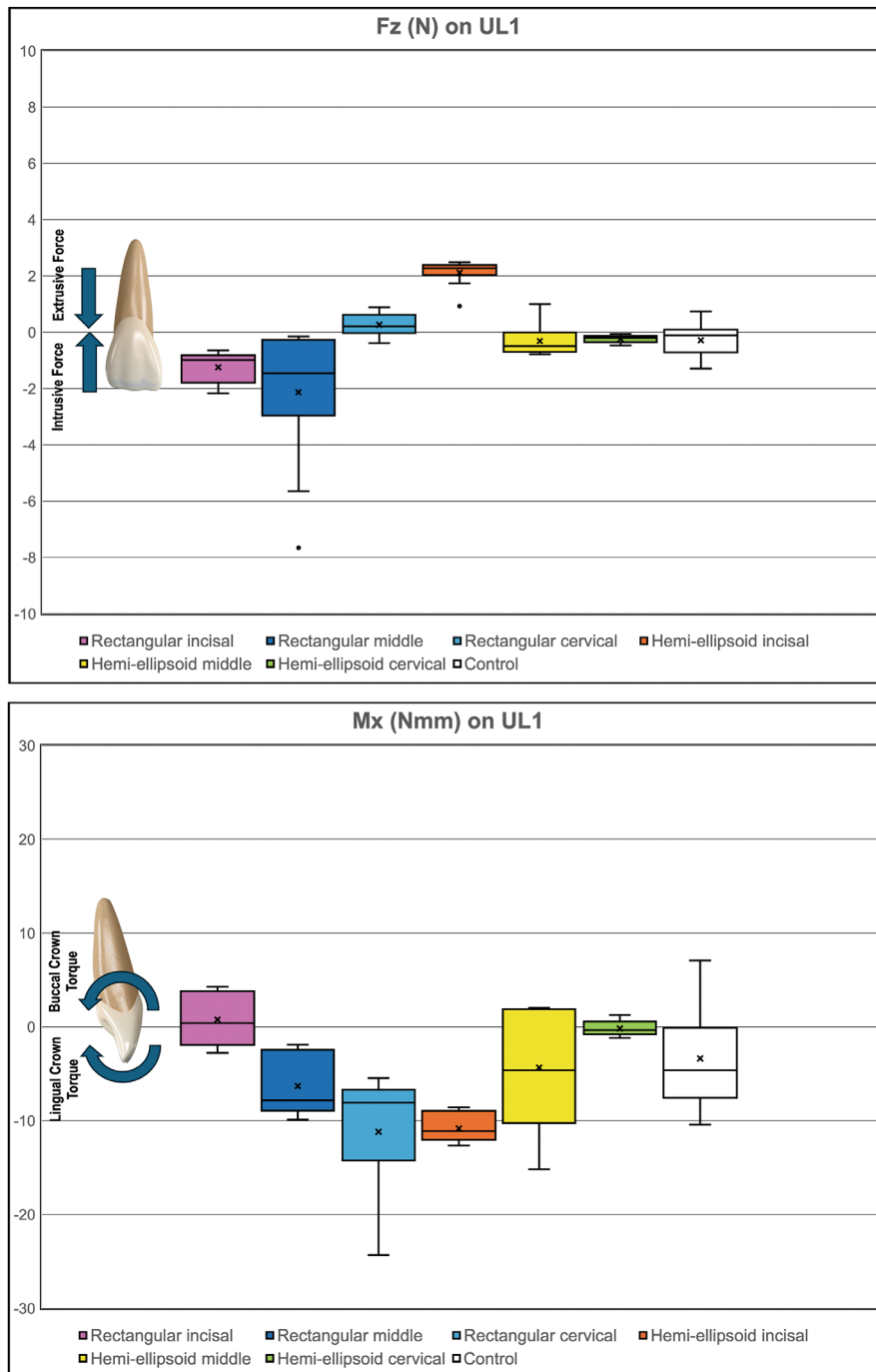


FIGURE 3 | Box and whisker plot depicting the distribution of the extrusive/intrusive forces (Fz) and bucco-lingual tipping moment (Mx) for the upper left central incisor (UL1).

yielded the most effective extrusive force with the least undesired moment.

Regarding the anchor teeth, the rectangular middle attachment design exposed the most intrusive forces to both the UL1 and UL3. The hemi-ellipsoid attachment design reduced the intrusive force on both. The bucco-lingual moment was most minimised on UL1 when using the rectangular cervical design and the hemi-ellipsoid cervical design. The bucco-lingual moment was most minimised on UL3 when using the rectangular middle design.

This study investigated the biomechanical aspects of dental extrusion using thermoplastic aligners with varying attachment shape and location to determine the efficacy of attachment designs on producing clinically desirable force systems. The ideal force system to obtain pure extrusion is an extrusive force with minimal bucco-lingual moment. The study revealed that the purest force system (i.e., greatest amount and direction of intended force/moment and least amount and direction of undesired force/moment) was the rectangular attachment in the middle third of the tooth.

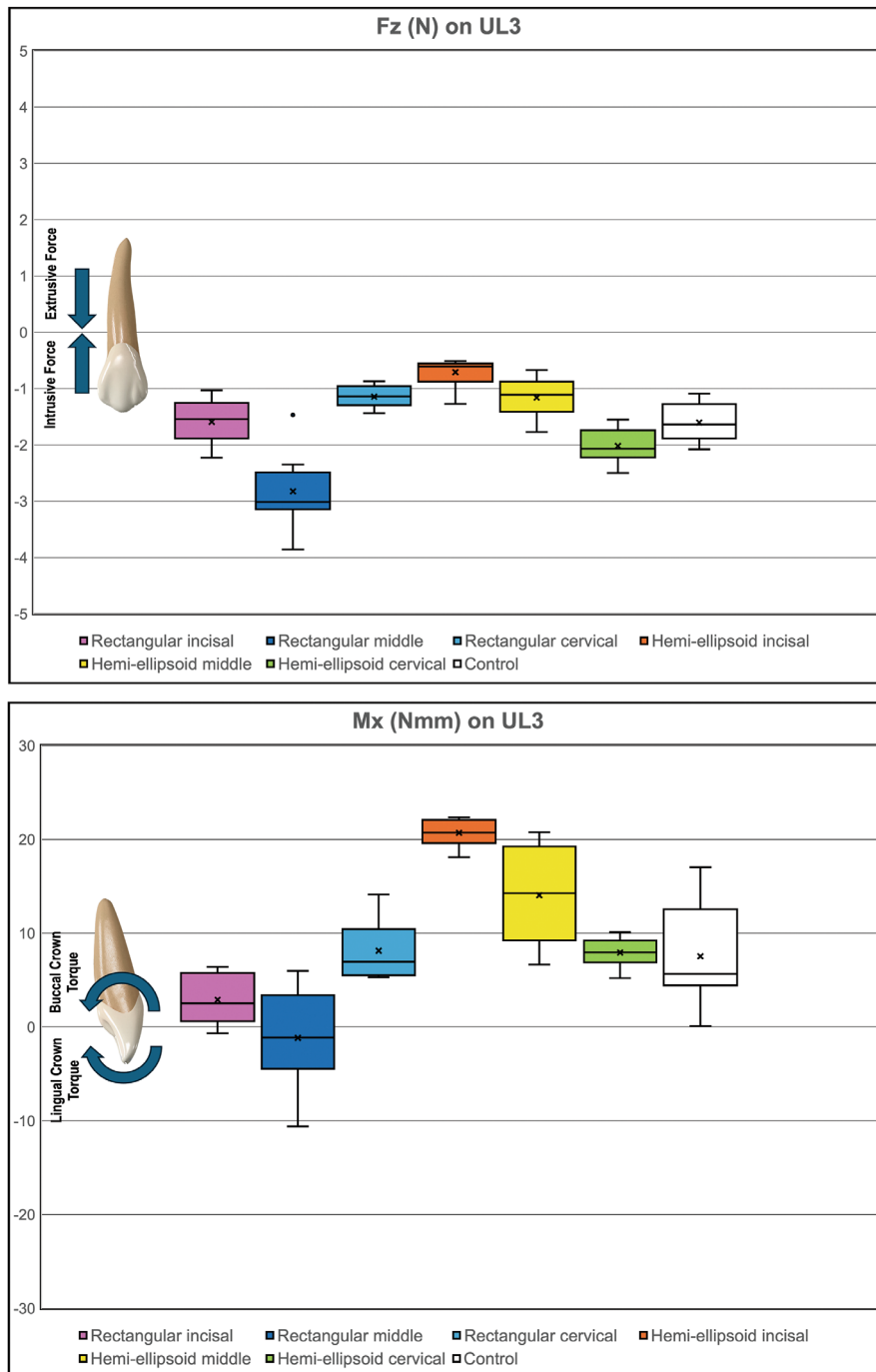


FIGURE 4 | Box and whisker plot depicting the distribution of the extrusive/intrusive forces (Fz) and bucco-lingual tipping moment (Mx) for the upper left canine (UL3).

Proffit proposed applying light and continuous forces for effective extrusion in the 35–60g range to safely and efficiently achieve extrusion [30]. The forces produced in this in vitro study ranged from 0 to 750g during the simulated extrusion of the UL2. These force levels reveal a discrepancy between what is clinically applicable and what is theoretically most effective. The goal of the present in vitro study was to describe the 3D force system accurately and precisely in all three planes of space rather than achieve specific clinical force values. The forces from the rectangular middle attachment were the purest. Since little is known about the clinical force levels provided by clear aligners in vivo, it is possible that both commercial and ‘in

house’ aligners deliver similarly high forces during extrusion of maxillary lateral incisors as observed here. As a result, the lost tracking that is commonly reported could result from reduced compliance rather than the extrusive force system delivered with the clear aligners.

The attachment design that was found to be most associated with clinically recommended values was the rectangular design located at the cervical third of the tooth. The force levels produced in this in vitro model were approximately 120g. Clinically, these forces would likely closely approximate Proffit’s recommended values due to the periodontal ligament (PDL),

and other biological factors mitigating the forces being delivered. Unfortunately, the rectangular attachment in the cervical third has the greatest unwanted moment associated with the extrusion. When achieving the most physiologically acceptable extrusion of the lateral incisor, the most undesired moment will also be produced on the tooth.

When analysing the effect of UL2 extrusion on the adjacent anchor teeth, the results were highly variable. When looking at similar studies conducted on predictability of extrusion of the incisors, similar variability was found. In a single-blind study analysing the extrusion of the maxillary lateral incisor by Groody, the results revealed a significantly lower predictability than originally postulated with averages of 73% [31]. Rossini, in another study measuring the forces and moments generated during extrusion claimed that it was very evident that more data and testing were needed to better understand both aligner's biomechanics and how to avoid the unwanted side effect movements [32].

The current study also examined the repeatability of the results from the same aligner and among the five different aligners. Result showed that nearly identical loads were obtained when the same aligner was tested. However, large variations were observed when different aligners were tested. This can be explained by the aligners being manually made. The aligners likely vary due to both the thermoforming process and manual trimming. Each was trimmed with a flat cut at the gingival margin.

This study has several limitations to consider. Being an in vitro study, it does not account for the effects of the PDL on the load experienced by the teeth. The level of extrusion force depends on the stiffness of the tissues surrounding the tooth root; theoretically, higher tissue stiffness results in a higher extrusion force. The in vitro device used in this study immobilised all teeth with a stiffness greater than that of natural periodontal support. As a result, our findings may overestimate the extrusive forces because the absence of the PDL likely reduces the extrusive force delivered to the tooth in vivo. Despite this potential overestimation, an extrusion force of a few Newtons does not produce noticeable tooth extrusion in clinical practice; therefore, the effect on the initial extrusion force is considered negligible. However, this study provides a good first estimation, and the relative moment-to-force ratios generated are reliable, demonstrating the biomechanical rationale for potential side effects observed clinically during treatment. Another limitation is that only the initial load was measured—for the first 10s—whereas in clinical practice, patients wear aligners for extended periods with an ever-changing load as the teeth move. Additionally, many other factors were not considered in this study, such as aligner materials, thickness, bacterial flora, material degradation, and other types of attachments. To further investigate these aspects, the load-extrusion relationship of the tooth needs to be quantified, which is currently unavailable. This represents a critical area for future studies to better understand the dynamics of extrusion force under various aligner designs. More studies are needed to increase the understanding of this technology.

Our study demonstrates that direct attachments dramatically change the forces and moments acting on teeth during CAT. Even minor modifications in the design and location of these

attachments can significantly affect treatment outcomes. This finding underscores the critical importance of precise attachment planning in CAT. As in-house aligner systems become increasingly popular, many clinicians may lack the extensive experience and scientific basis needed to optimise direct attachments effectively. Established clear aligner companies have been collecting data for decades to refine their attachment designs, but this information is not publicly available. Therefore, our study serves as a foundational step toward providing clinicians with evidence-based guidelines for attachment design and placement. By applying these guidelines, orthodontists can enhance the efficiency and predictability of CAT, especially when utilising in-house aligner systems. Our study aims to empower practitioners with insights that have previously been limited due to the proprietary nature of aligner companies' data.

5 | Conclusion

Varying the location and shape of attachment on the UL2 during extrusion has a significant effect on both the moments and forces generated by the thermoplastic aligners. The most effective attachment design to maximise extrusive forces and minimise unwanted moments was the rectangular attachment located in the middle third of the UL2. For the neighbouring UL1 and UL3, hemi-ellipsoid attachments located in the cervical third were found to be the most effective in minimising the reciprocal intrusive forces and unwanted moments.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. T. Weir, "Clear Aligners in Orthodontic Treatment," *Australian Dental Journal* 62, no. Suppl 1 (2017): 58–62.
2. H. D. Kesling, "The Philosophy of Tooth Positioning Appliance," *American Journal of Orthodontics and Dentofacial Orthopedics* 31 (1945): 297–304.
3. X. Phan and P. H. Ling, "Clinical Limitations of Invisalign," *Journal of the Canadian Dental Association* 73, no. 3 (2007): 263–266.
4. Y. M. Bichu, A. Alwafi, X. Liu, et al., "Advances in Orthodontic Clear Aligner Materials," *Bioactive Materials* 22 (2023): 384–403.
5. Y. Ke, Y. Zhu, and M. Zhu, "A Comparison of Treatment Effectiveness Between Clear Aligner and Fixed Appliance Therapies," *BMC Oral Health* 19, no. 1 (2019): 24.
6. D. W. White, K. C. Julien, H. Jacob, P. M. Campbell, and P. H. Buschang, "Discomfort Associated With Invisalign and Traditional Brackets: A Randomized, Prospective Trial," *Angle Orthodontist* 87, no. 6 (2017): 801–808.
7. S. M. Adel, I. Hansa, and N. R. Vaid, "Clear Aligner Therapy in Contemporary Orthodontics: A Scoping Review of Scholarly Literature," *APOS Trends in Orthodontics* 14, (2024): 3–27.
8. Y. M. Bichu, T. Weir, B. Zou, S. Adel, and N. R. Vaid, "Clear Aligner Therapy Concerns: Addressing Discrepancies Between Digitally

- Anticipated Outcomes and Clinical Ground Realities,” *Turkish Journal of Orthodontics* 37, no. 2 (2024): 130–139.
9. N. R. Vaid, W. Sabouni, B. Wilmes, Y. M. Bichu, D. P. Thakkar, and S. M. Adel, “Customized Adjuncts With Clear Aligner Therapy: “the Golden Circle Model” Explained!,” *Journal of the World Federation of Orthodontists* 11, no. 6 (2022): 216–225.
10. N. D. Kravitz, B. Dalloul, Y. A. Zaid, C. Shah, and N. R. Vaid, “What Percentage of Patients Switch From Invisalign to Braces? A Retrospective Study Evaluating the Conversion Rate, Number of Refinement Scans, and Length of Treatment,” *American Journal of Orthodontics and Dentofacial Orthopedics* 163, no. 4 (2023): 526–530.
11. N. D. Kravitz, B. Kusnoto, E. BeGole, A. Obrez, and B. Agran, “How Well Does Invisalign Work? A Prospective Clinical Study Evaluating the Efficacy of Tooth Movement With Invisalign,” *American Journal of Orthodontics and Dentofacial Orthopedics* 135, no. 1 (2009): 27–35.
12. N. Haouili, N. D. Kravitz, N. R. Vaid, D. J. Ferguson, and L. Makki, “Has Invisalign Improved? A Prospective Follow-Up Study on the Efficacy of Tooth Movement With Invisalign,” *American Journal of Orthodontics and Dentofacial Orthopedics* 158, no. 3 (2020): 420–425.
13. L. Galan-Lopez, J. Barcia-Gonzalez, and E. Plasencia, “A Systematic Review of the Accuracy and Efficiency of Dental Movements With Invisalign(R),” *Korean Journal of Orthodontics* 49, no. 3 (2019): 140–149.
14. Y. Y. Hong, T. Kang, M. Q. Zhou, J. Y. Zhong, and X. P. Chen, “Effect of Varying Auxiliaries on Maxillary Incisor Torque Control With Clear Aligners: A Finite Element Analysis,” *American Journal of Orthodontics and Dentofacial Orthopedics* 166, no. 1 (2024): 50–60.
15. “Align Technology Announces Invisalign® G8 With New Smartforce® Aligner Activation Features,” 2020, <https://investor.aligntech.com/news-releases/news-release-details/align-technology-announces-invisalign-g8-new-smartforce>.
16. “Align Technology Announces Next Series of Innovation With Invisalign(R) G7 and Clincheck Pro 5.0 Software,” 2016.
17. “Align Technology Announces Invisalign G6 Clinical Innovations For Orthodontic Treatment Of First Premolar Extractions,” 2014.
18. “Align Technology Announces Invisalign G5 Innovations for Treatment Of Deep Bite,” 2013.
19. “Align Technology Introduces Invisalign G4,” 2011.
20. “Align Technology Introduces Invisalign G3,” 2010.
21. M. Lear, A. Akbari, O. Robertson, et al., “In Vitro Comparison of Direct Attachment Shape and Size on the Orthodontic Forces and Moments Generated by Thermoplastic Aligners During Expansion,” *Orthodontics & Craniofacial Research* (2024). Epub ahead of print. doi:10.1111/ocr.12865.
22. J. Kawamura, K. Ojima, and R. Nanda, “Effect of Attachment Type on Distal Bodily Movement of the Maxillary Canine in Aligner Orthodontics: A Finite Element Study,” *Angle Orthodontist* 93, no. 5 (2023): 566–571.
23. C. Ayidağa and B. Kamiloğlu, “Effects of Variable Composite Attachment Shapes in Controlling Upper Molar Distalization With Aligners: A Nonlinear Finite Element Study,” *Journal of Healthcare Engineering* 2021 (2021): 1–8.
24. P. Laohachaiaroon, B. Samruajbenjakun, and E. Chaichanasiri, “Initial Displacement and Stress Distribution of Upper Central Incisor Extrusion With Clear Aligners and Various Shapes of Composite Attachments Using the Finite Element Method,” *Journal of Dentistry* 10, no. 6 (2022): 114.
25. R. Costa, F. C. Calheiros, R. Y. Ballester, and F. Gonçalves, “Effect of Three Different Attachment Designs in the Extrusive Forces Generated by Thermoplastic Aligners in the Maxillary Central Incisor,” *Dental Press Journal of Orthodontics* 25, no. 3 (2020): 46–53.
26. R. Savignano, R. Valentino, A. V. Razionale, A. Michelotti, S. Barone, and V. D’Antò, “Biomechanical Effects of Different Auxiliary-Aligner Designs for the Extrusion of an Upper Central Incisor: A Finite Element Analysis,” *Journal of Healthcare Engineering* 2019 (2019): 9687127.
27. D. Wang, H. Turkkahraman, J. Chen, B. Li, and Y. Liu, “Quantification of Orthodontic Loads on Teeth in the Correction of Canine Overeruption Using Different Archwire Designs,” *American Journal of Orthodontics and Dentofacial Orthopedics* 163, no. 1 (2023): e13–e21.
28. R. Nucera, C. Dolci, A. M. Bellocchio, et al., “Effects of Composite Attachments on Orthodontic Clear Aligners Therapy: A Systematic Review,” *Materials* 15, no. 2 (2022): 533.
29. M. Al-Nadawi, N. D. Kravitz, I. Hansa, L. Makki, D. J. Ferguson, and N. R. Vaid, “Effect of Clear Aligner Wear Protocol on the Efficacy of Tooth Movement,” *Angle Orthodontist* 91, no. 2 (2021): 157–163.
30. W. R. Proffit, H. Fields, B. Larson, and D. M. Sarver, *Contemporary Orthodontics-E-Book: Contemporary Orthodontics-E-Book USA*: Mosby, (2018).
31. J. T. Groody, S. J. Lindauer, N. D. Kravitz, et al., “Effect of Clear Aligner Attachment Design on Extrusion of Maxillary Lateral Incisors: A Multicenter, Single-Blind Randomized Clinical Trial,” *American Journal of Orthodontics and Dentofacial Orthopedics* 164, no. 5 (2023): 618–627.
32. G. Rossini, S. Modica, S. Parrini, A. Deregibus, and T. Castroflorio, “Incisors Extrusion With Clear Aligners Technique: A Finite Element Analysis Study,” *Applied Sciences* 11, no. 3 (2021): 1167.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.