

## Article

# Forces and Moments Generated by Direct Printed Aligners During Bodily Movement of a Maxillary Central Incisor

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## Abstract

The aim of this study was to compare the forces and moments exerted by thermoformed aligners (TFMs) and direct printed aligners (DPAs) on the maxillary left central incisor (21) and adjacent teeth (11, 22) during lingual bodily movement of tooth 21. Methods: An in vitro setup was used to quantify forces and moments on three incisors, which were segmented and fixed onto multi-axis force/moment transducers. TFM were fabricated using 0.76 mm-thick single-layer PET-G foils (ATMOS; American Orthodontics, Sheboygan, WI, USA) and multi-layer TPU foils (Zendura FLX; Bay Materials LLC, Fremont, CA, USA). DPAs were fabricated using TC-85 photopolymer resin (Graphy Inc., Seoul, Republic of Korea). Tooth 21 was planned for bodily displacement by 0.25 mm and 0.50 mm, and six force and moment components were measured on it and the adjacent teeth. Results: TC-85 generated lower forces and moments with fewer unintended forces and moments on the three teeth. TC-85 exerted 0.99 N and 1.53 N of mean lingual force on tooth 21 for 0.25 mm and 0.50 mm activations, respectively; ATMOS produced 3.82 N and 7.70 N, and Zendura FLX produced 3.00 N and 8.23 N of mean lingual force for the same activations, respectively. Bodily movement could not be achieved. Conclusions: The force systems generated by clear aligners are complex and unpredictable. DPA using TC-85 produced lower, more physiological force levels with fewer side effects, which may increase the predictability of tooth movement and enhance treatment outcome. The force levels generated by TFM were considered excessive and not physiologically compatible.

**Keywords:** tooth movement; aligners



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## 1. Introduction

Three-dimensional (3D) printing technology has become an integral part of modern orthodontics, offering enhanced customization, workflow efficiency, and precision. Initially adopted for the fabrication of dental models, 3D printing has more recently expanded to the realm of surgical guides, temporomandibular joint splints, indirect bonding trays, and custom brackets [1–5]. Another emerging application of 3D printing in orthodontics is the production of clear aligners.

Over the past two decades, clear aligner therapy (CAT) has become a popular treatment modality, especially for patients seeking an esthetic and comfortable orthodontic appliance. Advances in computer-aided design and manufacturing technology have improved the clinical efficacy of CAT [6]; however, its overall performance remains inferior to that of

fixed appliances [7]. Therefore, there is a need to develop new materials and workflows to improve patient and clinician experience with this evolving treatment modality.

The conventional method for fabricating clear aligners has involved the thermoforming process, which is error-prone, costly, time-consuming, and environmentally wasteful [8]. Recently, the development of a clear photocurable resin has enabled the production of direct printed aligners (DPA), promising improved accuracy and precision, simplified workflow, and reduced waste. However, there are currently few published studies that have evaluated the forces and moments generated by this new material during simulated orthodontic tooth movement [9–11]. An improved understanding of the biomechanics involved in CAT using DPA may lead to more predictable and biologically harmonious force application, enhancing treatment outcome and efficiency while minimizing iatrogenic tissue damage.

The aim of this study was to evaluate the forces and moments exerted by clear aligners during in vitro simulated lingual bodily movement of the maxillary left central incisor. The forces and moments exerted on the central incisor and its adjacent teeth were compared between thermoformed aligners (TFM) and DPA at two activation amounts. The moment-to-force (M/F) ratios of the aligners were also calculated to determine if bodily movement could be achieved with the tested materials.

## 2. Materials and Methods

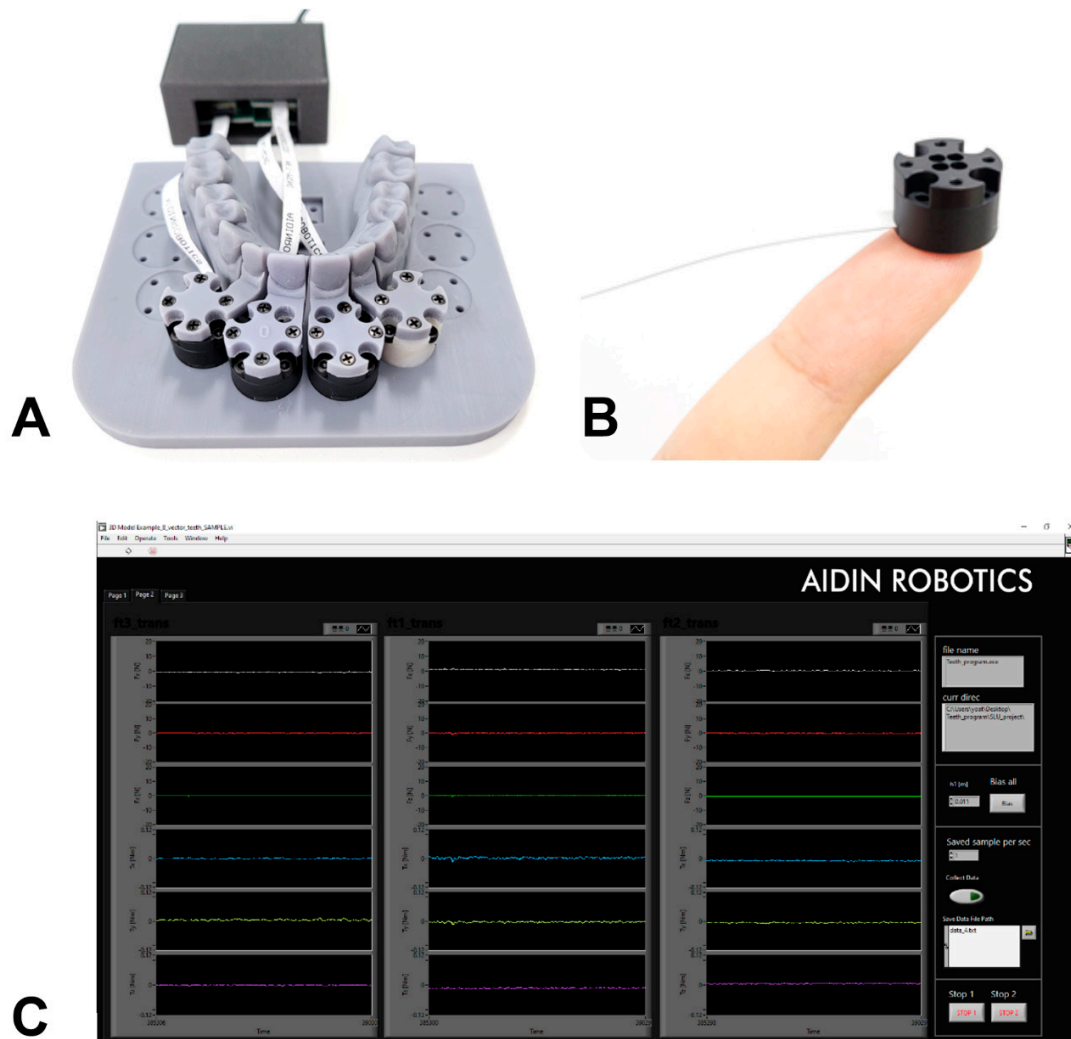
### 2.1. Experimental Apparatus

An in vitro hardware/software setup was used to quantify the forces and moments generated by clear aligners on maxillary teeth, as previously described (Figure 1) [9–11]. The hardware setup consisted of a 3D-printed base plate and segmented maxillary teeth. The maxillary arch was 3D printed from a digital scan of a typodont with ideal alignment. Three AFT20-D15 multi-axis force/moment transducers (Aidin Robotics Inc., Anyang, Republic of Korea) were mounted to the base plate and fixed to the simulated teeth. The AFT20-D15 sensor was validated against the Nano25 sensor (ATI Industrial Automation, Apex, NC, USA) by the manufacturer and was found to be comparable in its accuracy (<99%). The maxillary left central incisor (tooth 21) was printed with a 0.50 mm displacement in the labial direction to simulate the restoration of ideal alignment through lingual bodily movement. The test apparatus was placed in a semi-enclosed chamber to maintain a temperature of 37 °C to simulate the oral environment.

### 2.2. Aligner Fabrication

Sixty clear aligners were divided into six groups of ten aligners each, based on material types and activation amounts. uDesign 6.0 software (uLab Systems Inc., Memphis, TN, USA) was used to design aligners with 0.25 mm and 0.50 mm activations for lingual bodily movement of tooth 21 (Figure 2).

For TFM, the corresponding resin models were 3D printed with SprintRay Pro 95 (SprintRay Inc., Los Angeles, CA, USA) in vertical orientation in 100 µm layers. Next, aligners were fabricated using 0.76 mm thick sheets of ATMOS (American Orthodontics, Sheboygan, WI, USA) and Zendura FLX (Bay Materials LLC, Fremont, CA, USA) materials through the thermoforming process with a Biostar machine (Scheu Dental GmbH, Iserlohn, Germany) according to the manufacturers' instructions (Code 123 and Code 162, respectively). The aligners were trimmed flush with the gingival margins. ATMOS is advertised as a single-layer PET-G polymer. Zendura FLX is a multi-layer TPU plastic that consists of two hard outer shells and an inner elastomeric layer, the exact composition of which is proprietary.



**Figure 1.** In vitro experimental apparatus. (A) Hardware setup. (B) Multi-axis force/moment transducer. (C) Software setup for data collection and visualization.



**Figure 2.** The maxillary arch setup created on uDesign 6.0.

For DPA (Figure 3), uDesign 6.0 was used to generate aligner files with 0.50 mm thickness and 0.05 mm offset from tooth surfaces, with edges extending to the gingival margins. The thickness was set to 0.50 mm to represent the post-thermoforming thickness of TFM, and the offset was set to 0.05 mm to allow ease of application [12,13]. The aligner files were imported into Uniz Maker (Uniz Technology LLC, San Diego, CA, USA) for 3D printing preparation and subsequently 3D printed with SprintRay Pro 95 using TC-85 resin (Graphy Inc., Seoul, Republic of Korea) in 100  $\mu$ m build layers. Afterwards, the aligners were detached from the build platform and cleaned of residual resin using centrifugation for 6 min. The aligners were post-cured using Tera Harz Cure (Graphy Inc., Seoul, Republic of Korea) with UV light under nitrogen gas for 14 min.



**Figure 3.** A 3D-printed clear aligner, fabricated using TC-85 photocurable resin.

### 2.3. Data Collection

Upon fabrication, the aligners were stored in airtight bags until they were inserted into the test apparatus at 37 °C. For each measurement, the force and moment values were zeroed prior to data collection to eliminate mechanical influences from installation and previous appliance insertion.

Shortly before insertion, TFMs were placed in ambient room temperature (18 °C), whereas DPAs were placed in a warm water bath set at a temperature of 69.4 °C for 5 s. This was to simulate the clinical insertion protocol for each material type; TFMs are typically placed into the oral environment directly from ambient settings, whereas DPAs printed from TC-85 are recommended by the resin manufacturer to be heated in warm water prior to insertion to fully take advantage of their shape memory property. The temperature of the water bath (69.4 °C) corresponds to the glass transition temperature ( $T_g$ ) of TC-85 [14].

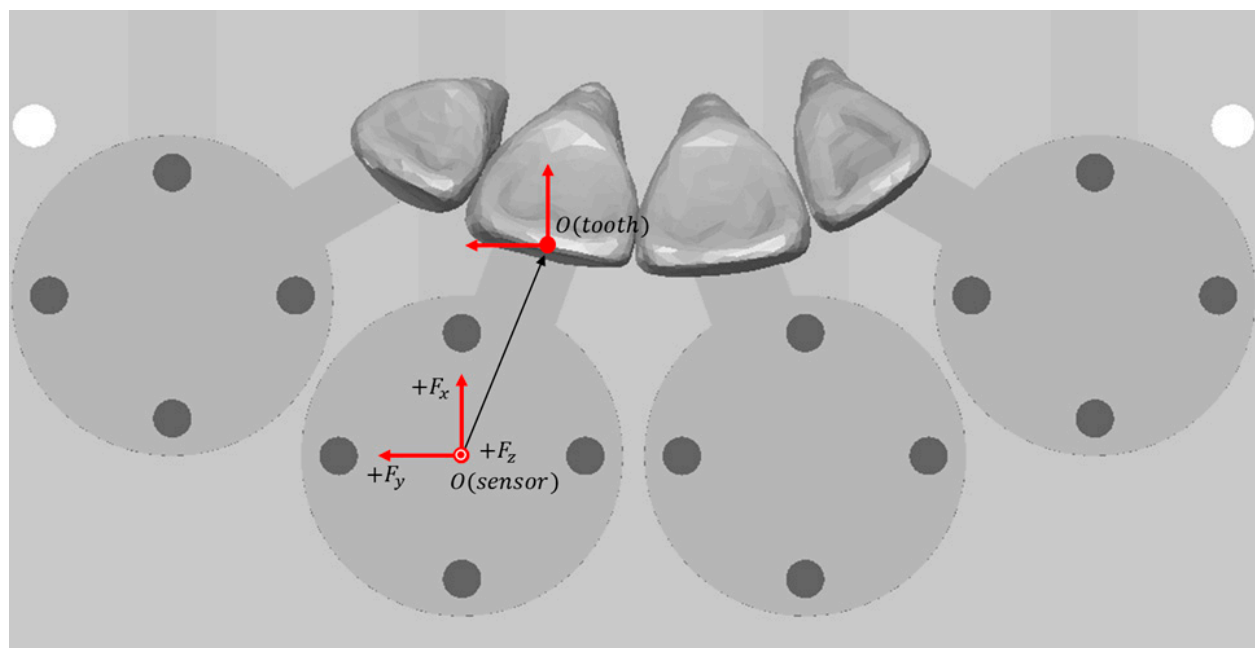
All aligners were inserted in the test apparatus, and then the forces and moments were measured at a sampling rate of 600 Hz. Following initial stabilization of the sensor



readings, the final 8.3 s of data were recorded for subsequent analysis. The forces and moments in the x, y, and z directions were defined as shown in Table 1 and Figure 4.

**Table 1.** Definitions of forces and moments in the x, y, and z axes.

|       |                                |
|-------|--------------------------------|
| $F_x$ | Force—Faciolingual (F-L)       |
| $F_y$ | Force—Mesiodistal (M-D)        |
| $F_z$ | Force—Occlusogingival (O-G)    |
| $M_x$ | Moment—Crown angulation (M-D)  |
| $M_y$ | Moment—Crown inclination (F-L) |
| $M_z$ | Moment—Rotation (M-D)          |



**Figure 4.** The coordinate system used for the experimental apparatus. The directions of forces in the x, y, and z axes are as shown. The directions of moments follow the right-hand rule. Force and moment readings from the sensors were transformed to the estimated center of resistance of each respective tooth.

#### 2.4. Statistical Analysis

The forces and moments for the x, y, and z axes were analyzed with respect to the estimated centers of resistance of the three measured teeth [15–19], and their means and standard deviations were summarized. For each tooth, the forces and moments from each activation amount were compared across materials. The differences in the forces and moments by material type for each activation amount were also compared. Comparisons were performed using analysis of variance via the PROC ANOVA procedure, with Bonferroni corrections applied for post hoc multiple comparisons. These statistical analyses were conducted using SAS version 9.3 (SAS Institute Inc., Cary, NC, USA). Significance tests were performed by using a two-tailed hypothesis, and the level of significance ( $\alpha$ ) was set to 0.05. A post hoc power analysis was performed using GPower version 3.1.9.7 for the primary outcome (0.25 mm of activation of tooth 21) to assess the achieved power.

To evaluate the directional precision of the force system produced by each aligner group on tooth 21, the angular deviation between the measured force vector and the intended force vector was calculated. Additionally, the off-axis force magnitude was

calculated to quantify the magnitude of the component of the force not aligned with the intended vector. To calculate the M/F ratios for tooth 21, the faciolingual moment (My) and faciolingual force (Fx) were transformed to the facial axis of the clinical crown (FA point), and My was divided by Fx. These computations were performed using MATLAB R2022a (MathWorks, Natick, MA, USA).

### 3. Results

#### 3.1. Forces and Moments

The comparisons of initial forces and moments exerted on each tooth by material type are given in Tables 2–4. All the mean forces and moments were significantly different between the three material types at every activation amount ( $p < 0.05$ ). The comparisons of initial forces and moments exerted on the tooth 21, 11, and 22 by activation amount are given in Tables 5–7, respectively. All the mean forces and moments were significantly different between the activation amounts for each material type ( $p < 0.05$ ). For the faciolingual force (Fx) at 0.25 mm activation on tooth 21, a large effect size was observed for the ANOVA (Cohen's  $f = 0.67$ ). With a sample size of ten aligners per group and a significance level ( $\alpha$ ) of 0.05, the achieved post hoc power ( $1 - \beta$ ) was 88%, indicating that the sample size was sufficient to detect the observed differences between the groups.

**Table 2.** Comparisons of initial forces and moments exerted on the maxillary left central incisor (21) by material type for 0.25 mm and 0.50 mm activations.

|          | 0.25 mm Activation |   |   |        |             |   |   |        |           |   |   |      | <i>p</i> -Value |        |        |
|----------|--------------------|---|---|--------|-------------|---|---|--------|-----------|---|---|------|-----------------|--------|--------|
|          | ATMOS              |   |   |        | Zendura FLX |   |   |        | TC-85     |   |   |      |                 |        |        |
|          | Mean ± SD          |   |   |        | Mean ± SD   |   |   |        | Mean ± SD |   |   |      | a               | b      | c      |
| Fx (N)   | 3.82               | L | ± | 2.33   | 3.00        | L | ± | 2.22   | 0.99      | L | ± | 0.33 | <0.001          | <0.001 | <0.001 |
| Fy (N)   | 0.65               | M | ± | 8.06   | 5.97        | M | ± | 6.98   | 0.64      | M | ± | 0.39 | <0.001          | <0.001 | <0.001 |
| Fz (N)   | 4.09               | O | ± | 2.30   | 3.32        | O | ± | 2.88   | 0.10      | G | ± | 0.18 | <0.001          | <0.001 | <0.001 |
| Mx (Nmm) | 75.95              | M | ± | 36.86  | 61.45       | M | ± | 39.98  | 2.53      | M | ± | 2.72 | <0.001          | <0.001 | <0.001 |
| My (Nmm) | 45.53              | L | ± | 27.35  | 33.74       | L | ± | 27.66  | 4.27      | L | ± | 1.75 | <0.001          | <0.001 | <0.001 |
| Mz (Nmm) | 82.20              | D | ± | 91.89  | 27.41       | D | ± | 81.65  | 14.29     | D | ± | 3.31 | <0.001          | <0.001 | <0.001 |
|          | 0.50 mm Activation |   |   |        |             |   |   |        |           |   |   |      | <i>p</i> -Value |        |        |
|          | ATMOS              |   |   |        | Zendura FLX |   |   |        | TC-85     |   |   |      |                 |        |        |
|          | Mean ± SD          |   |   |        | Mean ± SD   |   |   |        | Mean ± SD |   |   |      | a               | b      | c      |
| Fx (N)   | 7.70               | L | ± | 4.91   | 8.23        | L | ± | 5.61   | 1.53      | L | ± | 0.40 | <0.001          | <0.001 | <0.001 |
| Fy (N)   | 3.54               | M | ± | 7.73   | 1.84        | M | ± | 7.37   | 0.32      | M | ± | 0.45 | <0.001          | <0.001 | <0.001 |
| Fz (N)   | 18.94              | G | ± | 13.85  | 14.27       | G | ± | 17.10  | 0.06      | O | ± | 0.27 | <0.001          | <0.001 | <0.001 |
| Mx (Nmm) | 290.06             | D | ± | 215.70 | 215.45      | D | ± | 261.24 | 5.29      | M | ± | 3.61 | <0.001          | <0.001 | <0.001 |
| My (Nmm) | 66.22              | F | ± | 75.84  | 39.82       | F | ± | 93.82  | 9.90      | L | ± | 3.12 | <0.001          | <0.001 | <0.001 |
| Mz (Nmm) | 129.16             | D | ± | 75.69  | 148.13      | D | ± | 82.49  | 21.66     | D | ± | 4.73 | <0.001          | <0.001 | <0.001 |

a—ATMOS vs. Zendura FLX; b—Zendura FLX vs. TC-85; c—ATMOS vs. TC-85. F—Facial; L—Lingual; M—Mesial; D—Distal; O—Occlusal; G—Gingival.

**Table 3.** Comparisons of initial forces and moments exerted on the maxillary right central incisor (11) by material type for 0.25 mm and 0.50 mm activations.

|          | 0.25 mm Activation |   |   |       |             |   |   |       |           |   |   |      | <i>p</i> -Value |        |        |
|----------|--------------------|---|---|-------|-------------|---|---|-------|-----------|---|---|------|-----------------|--------|--------|
|          | ATMOS              |   |   |       | Zendura FLX |   |   |       | TC-85     |   |   |      |                 |        |        |
|          | Mean ± SD          |   |   |       | Mean ± SD   |   |   |       | Mean ± SD |   |   |      | a               | b      | c      |
| Fx (N)   | 2.01               | L | ± | 0.49  | 1.59        | L | ± | 0.37  | 0.52      | L | ± | 0.18 | <0.001          | <0.001 | <0.001 |
| Fy (N)   | 7.61               | D | ± | 2.03  | 8.88        | D | ± | 1.07  | 0.92      | D | ± | 0.54 | <0.001          | <0.001 | <0.001 |
| Fz (N)   | 1.47               | O | ± | 0.72  | 0.28        | O | ± | 0.35  | 0.16      | O | ± | 0.10 | <0.001          | <0.001 | <0.001 |
| Mx (Nmm) | 5.49               | D | ± | 5.14  | 1.18        | D | ± | 4.85  | 7.60      | M | ± | 1.46 | <0.001          | <0.001 | <0.001 |
| My (Nmm) | 28.97              | L | ± | 6.55  | 17.68       | L | ± | 3.79  | 4.71      | L | ± | 1.13 | <0.001          | <0.001 | <0.001 |
| Mz (Nmm) | 90.83              | D | ± | 22.67 | 105.50      | D | ± | 12.49 | 13.19     | D | ± | 5.78 | <0.001          | <0.001 | <0.001 |
|          | 0.50 mm Activation |   |   |       |             |   |   |       |           |   |   |      | <i>p</i> -Value |        |        |
|          | ATMOS              |   |   |       | Zendura FLX |   |   |       | TC-85     |   |   |      |                 |        |        |
|          | Mean ± SD          |   |   |       | Mean ± SD   |   |   |       | Mean ± SD |   |   |      | a               | b      | c      |
| Fx (N)   | 2.58               | L | ± | 0.76  | 2.25        | L | ± | 0.89  | 0.51      | L | ± | 0.22 | <0.001          | <0.001 | <0.001 |
| Fy (N)   | 7.29               | D | ± | 1.81  | 5.40        | D | ± | 2.74  | 1.37      | D | ± | 0.76 | <0.001          | <0.001 | <0.001 |
| Fz (N)   | 0.94               | O | ± | 0.43  | 0.63        | O | ± | 0.48  | 0.09      | G | ± | 0.10 | <0.001          | <0.001 | <0.001 |
| Mx (Nmm) | 6.04               | M | ± | 7.08  | 4.90        | M | ± | 5.94  | 10.91     | M | ± | 3.04 | <0.001          | <0.001 | <0.001 |
| My (Nmm) | 21.41              | L | ± | 4.26  | 16.79       | L | ± | 6.29  | 2.98      | L | ± | 1.72 | <0.001          | <0.001 | <0.001 |
| Mz (Nmm) | 92.50              | D | ± | 19.80 | 71.79       | D | ± | 29.93 | 19.97     | D | ± | 9.46 | <0.001          | <0.001 | <0.001 |

a—ATMOS vs. Zendura FLX; b—Zendura FLX vs. TC-85; c—ATMOS vs. TC-85. F—Facial; L—Lingual; M—Mesial; D—Distal; O—Occlusal; G—Gingival.

**Table 4.** Comparisons of initial forces and moments exerted on the maxillary left lateral incisor (22) by material type for 0.25 mm and 0.50 mm activations.

|          | 0.25 mm Activation |   |   |       |             |   |   |       |           |   |   | <i>p</i> -Value |        |        |        |
|----------|--------------------|---|---|-------|-------------|---|---|-------|-----------|---|---|-----------------|--------|--------|--------|
|          | ATMOS              |   |   |       | Zendura FLX |   |   |       | TC-85     |   |   |                 |        |        |        |
|          | Mean ± SD          |   |   |       | Mean ± SD   |   |   |       | Mean ± SD |   |   | a               | b      | c      |        |
| Fx (N)   | 0.86               | L | ± | 2.11  | 0.21        | L | ± | 0.84  | 0.34      | F | ± | 0.55            | <0.001 | <0.001 | <0.001 |
| Fy (N)   | 0.63               | D | ± | 3.47  | 0.34        | M | ± | 0.81  | 0.16      | D | ± | 0.40            | <0.001 | <0.001 | <0.001 |
| Fz (N)   | 1.05               | O | ± | 1.59  | 1.02        | O | ± | 1.61  | 0.21      | G | ± | 0.12            | <0.001 | <0.001 | <0.001 |
| Mx (Nmm) | 17.49              | M | ± | 25.91 | 16.90       | M | ± | 23.18 | 3.42      | M | ± | 0.97            | <0.001 | <0.001 | <0.001 |
| My (Nmm) | 20.62              | L | ± | 23.66 | 15.28       | L | ± | 15.50 | 0.70      | F | ± | 1.96            | <0.001 | <0.001 | <0.001 |
| Mz (Nmm) | 18.39              | D | ± | 72.60 | 4.64        | D | ± | 11.87 | 5.46      | D | ± | 4.10            | <0.001 | <0.001 | <0.001 |
|          | 0.50 mm Activation |   |   |       |             |   |   |       |           |   |   | <i>p</i> -Value |        |        |        |
|          | ATMOS              |   |   |       | Zendura FLX |   |   |       | TC-85     |   |   |                 |        |        |        |
|          | Mean ± SD          |   |   |       | Mean ± SD   |   |   |       | Mean ± SD |   |   | a               | b      | c      |        |
| Fx (N)   | 0.54               | F | ± | 0.58  | 0.41        | F | ± | 0.54  | 0.51      | F | ± | 0.28            | <0.001 | <0.001 | <0.001 |
| Fy (N)   | 0.51               | M | ± | 0.42  | 0.93        | M | ± | 0.58  | 0.07      | M | ± | 0.25            | <0.001 | <0.001 | <0.001 |
| Fz (N)   | 0.19               | O | ± | 0.23  | 0.32        | O | ± | 0.27  | 0.15      | G | ± | 0.13            | <0.001 | <0.001 | <0.001 |
| Mx (Nmm) | 6.30               | M | ± | 1.27  | 5.52        | M | ± | 2.71  | 3.09      | M | ± | 1.53            | <0.001 | <0.001 | <0.001 |
| My (Nmm) | 8.27               | L | ± | 3.21  | 5.83        | L | ± | 5.22  | 2.73      | F | ± | 1.46            | <0.001 | <0.001 | <0.001 |
| Mz (Nmm) | 5.38               | M | ± | 8.85  | 6.95        | M | ± | 8.88  | 3.38      | D | ± | 3.31            | <0.001 | <0.001 | <0.001 |

a—ATMOS vs. Zendura FLX; b—Zendura FLX vs. TC-85; c—ATMOS vs. TC-85. F—Facial; L—Lingual; M—Mesial; D—Distal; O—Occlusal; G—Gingival.

**Table 5.** Comparisons of initial forces and moments exerted on the maxillary left central incisor (21) by activation amount for ATMOS, Zendura FLX, and TC-85 materials.

|          | ATMOS       |   |   |       |           |   |   |        | <i>p</i> -Value |
|----------|-------------|---|---|-------|-----------|---|---|--------|-----------------|
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |        |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |        |                 |
| Fx (N)   | 3.82        | L | ± | 2.33  | 7.70      | L | ± | 4.91   | <0.001          |
| Fy (N)   | 0.65        | M | ± | 8.06  | 3.54      | M | ± | 7.73   | <0.001          |
| Fz (N)   | 4.09        | O | ± | 2.30  | 18.94     | G | ± | 13.85  | <0.001          |
| Mx (Nmm) | 75.95       | M | ± | 36.86 | 290.06    | D | ± | 215.70 | <0.001          |
| My (Nmm) | 45.53       | L | ± | 27.35 | 66.22     | F | ± | 75.84  | <0.001          |
| Mz (Nmm) | 82.20       | D | ± | 91.89 | 129.16    | D | ± | 75.69  | <0.001          |
|          | Zendura FLX |   |   |       |           |   |   |        | <i>p</i> -Value |
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |        |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |        |                 |
| Fx (N)   | 3.00        | L | ± | 2.22  | 8.23      | L | ± | 5.61   | <0.001          |
| Fy (N)   | 5.97        | M | ± | 6.98  | 1.84      | M | ± | 7.37   | <0.001          |
| Fz (N)   | 3.32        | O | ± | 2.88  | 14.27     | G | ± | 17.10  | <0.001          |
| Mx (Nmm) | 61.45       | M | ± | 39.98 | 215.45    | D | ± | 261.24 | <0.001          |
| My (Nmm) | 33.74       | L | ± | 27.66 | 39.82     | F | ± | 93.82  | <0.001          |
| Mz (Nmm) | 27.41       | D | ± | 81.65 | 148.13    | D | ± | 82.49  | <0.001          |
|          | TC-85       |   |   |       |           |   |   |        | <i>p</i> -Value |
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |        |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |        |                 |
| Fx (N)   | 0.99        | L | ± | 0.33  | 1.53      | L | ± | 0.40   | <0.001          |
| Fy (N)   | 0.64        | M | ± | 0.39  | 0.32      | M | ± | 0.45   | <0.001          |
| Fz (N)   | 0.10        | G | ± | 0.18  | 0.06      | O | ± | 0.27   | <0.001          |
| Mx (Nmm) | 2.53        | M | ± | 2.72  | 5.29      | M | ± | 3.61   | <0.001          |
| My (Nmm) | 4.27        | L | ± | 1.75  | 9.90      | L | ± | 3.12   | <0.001          |
| Mz (Nmm) | 14.29       | D | ± | 3.31  | 21.66     | D | ± | 4.73   | <0.001          |

F—Facial; L—Lingual; M—Mesial; D—Distal; O—Occlusal; G—Gingival.

**Table 6.** Comparisons of initial forces and moments exerted on the maxillary right central incisor (11) by activation amount for ATMOS, Zendura FLX, and TC-85 materials.

|          | ATMOS     |   |   |       |           |   |   |       | <i>p</i> -Value |
|----------|-----------|---|---|-------|-----------|---|---|-------|-----------------|
|          | 0.25 mm   |   |   |       | 0.50 mm   |   |   |       |                 |
|          | Mean ± SD |   |   |       | Mean ± SD |   |   |       |                 |
| Fx (N)   | 2.01      | L | ± | 0.49  | 2.58      | L | ± | 0.76  | <0.001          |
| Fy (N)   | 7.61      | D | ± | 2.03  | 7.29      | D | ± | 1.81  | <0.001          |
| Fz (N)   | 1.47      | O | ± | 0.72  | 0.94      | O | ± | 0.43  | <0.001          |
| Mx (Nmm) | 5.49      | D | ± | 5.14  | 6.04      | M | ± | 7.08  | <0.001          |
| My (Nmm) | 28.97     | L | ± | 6.55  | 21.41     | L | ± | 4.26  | <0.001          |
| Mz (Nmm) | 90.83     | D | ± | 22.67 | 92.50     | D | ± | 19.80 | <0.001          |



**Table 6.** *Cont.*

|          | Zendura FLX |   |   |       |           |   |   |       | <i>p</i> -Value |
|----------|-------------|---|---|-------|-----------|---|---|-------|-----------------|
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |       |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |       |                 |
|          |             |   |   |       |           |   |   |       |                 |
| Fx (N)   | 1.59        | L | ± | 0.37  | 2.25      | L | ± | 0.89  | <0.001          |
| Fy (N)   | 8.88        | D | ± | 1.07  | 5.40      | D | ± | 2.74  | <0.001          |
| Fz (N)   | 0.28        | O | ± | 0.35  | 0.63      | O | ± | 0.48  | <0.001          |
| Mx (Nmm) | 1.18        | D | ± | 4.85  | 4.90      | M | ± | 5.94  | <0.001          |
| My (Nmm) | 17.68       | L | ± | 3.79  | 16.79     | L | ± | 6.29  | <0.001          |
| Mz (Nmm) | 105.50      | D | ± | 12.49 | 71.79     | D | ± | 29.93 | <0.001          |
|          | TC-85       |   |   |       |           |   |   |       | <i>p</i> -Value |
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |       |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |       |                 |
|          |             |   |   |       |           |   |   |       |                 |
| Fx (N)   | 0.52        | L | ± | 0.18  | 0.51      | L | ± | 0.22  | <0.001          |
| Fy (N)   | 0.92        | D | ± | 0.54  | 1.37      | D | ± | 0.76  | <0.001          |
| Fz (N)   | 0.16        | O | ± | 0.10  | 0.09      | G | ± | 0.10  | <0.001          |
| Mx (Nmm) | 7.60        | M | ± | 1.46  | 10.91     | M | ± | 3.04  | <0.001          |
| My (Nmm) | 4.71        | L | ± | 1.13  | 2.98      | L | ± | 1.72  | <0.001          |
| Mz (Nmm) | 13.19       | D | ± | 5.78  | 19.97     | D | ± | 9.46  | <0.001          |

F—Facial; L—Lingual; M—Mesial; D—Distal; O—Occlusal; G—Gingival.

**Table 7.** Comparisons of initial forces and moments exerted on the maxillary left lateral incisor (22) by activation amount for ATMOS, Zendura FLX, and TC-85 materials.

|          | ATMOS       |   |   |       |           |   |   |      | <i>p</i> -Value |
|----------|-------------|---|---|-------|-----------|---|---|------|-----------------|
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |      |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |      |                 |
|          |             |   |   |       |           |   |   |      |                 |
| Fx (N)   | 0.86        | L | ± | 2.11  | 0.54      | F | ± | 0.58 | <0.001          |
| Fy (N)   | 0.63        | D | ± | 3.47  | 0.51      | M | ± | 0.42 | <0.001          |
| Fz (N)   | 1.05        | O | ± | 1.59  | 0.19      | O | ± | 0.23 | <0.001          |
| Mx (Nmm) | 17.49       | M | ± | 25.91 | 6.30      | M | ± | 1.27 | <0.001          |
| My (Nmm) | 20.62       | L | ± | 23.66 | 8.27      | L | ± | 3.21 | <0.001          |
| Mz (Nmm) | 18.39       | D | ± | 72.60 | 5.38      | M | ± | 8.85 | <0.001          |
|          | Zendura FLX |   |   |       |           |   |   |      | <i>p</i> -Value |
|          | 0.25 mm     |   |   |       | 0.50 mm   |   |   |      |                 |
|          | Mean ± SD   |   |   |       | Mean ± SD |   |   |      |                 |
|          |             |   |   |       |           |   |   |      |                 |
| Fx (N)   | 0.21        | L | ± | 0.84  | 0.41      | F | ± | 0.54 | <0.001          |
| Fy (N)   | 0.34        | M | ± | 0.81  | 0.93      | M | ± | 0.58 | <0.001          |
| Fz (N)   | 1.02        | O | ± | 1.61  | 0.32      | O | ± | 0.27 | <0.001          |
| Mx (Nmm) | 16.90       | M | ± | 23.18 | 5.52      | M | ± | 2.71 | <0.001          |
| My (Nmm) | 15.28       | L | ± | 15.50 | 5.83      | L | ± | 5.22 | <0.001          |
| Mz (Nmm) | 4.64        | D | ± | 11.87 | 6.95      | M | ± | 8.88 | <0.001          |

Table 7. *Cont.*

|          | TC-85         |   |       |      |               |   |       |      | <i>p</i> -Value |
|----------|---------------|---|-------|------|---------------|---|-------|------|-----------------|
|          | 0.25 mm       |   |       |      | 0.50 mm       |   |       |      |                 |
|          | Mean $\pm$ SD |   |       |      | Mean $\pm$ SD |   |       |      |                 |
| Fx (N)   | 0.34          | F | $\pm$ | 0.55 | 0.51          | F | $\pm$ | 0.28 | <0.001          |
| Fy (N)   | 0.16          | D | $\pm$ | 0.40 | 0.07          | M | $\pm$ | 0.25 | <0.001          |
| Fz (N)   | 0.21          | G | $\pm$ | 0.12 | 0.15          | G | $\pm$ | 0.13 | <0.001          |
| Mx (Nmm) | 3.42          | M | $\pm$ | 0.97 | 3.09          | M | $\pm$ | 1.53 | <0.001          |
| My (Nmm) | 0.70          | F | $\pm$ | 1.96 | 2.73          | F | $\pm$ | 1.46 | <0.001          |
| Mz (Nmm) | 5.46          | D | $\pm$ | 4.10 | 3.38          | D | $\pm$ | 3.31 | <0.001          |

F—Facial; L—Lingual; M—Mesial; D—Distal; O—Occlusal; G—Gingival.

The magnitude of lingual force experienced by tooth 21 increased with increasing activation of lingual bodily movement. For ATMOS, a two-fold increase in activation from 0.25 mm to 0.50 mm resulted in a two-fold increase in the mean lingual force from 3.82 N to 7.70 N; for Zendura FLX, the same increase in activation resulted in a 2.7-fold increase in mean lingual force from 3.00 N to 8.23 N; and for TC-85, the same increase in activation resulted in a 1.5-fold increase in mean lingual force from 0.99 N to 1.53 N.

In addition to expected lingual forces, the aligners generated unplanned forces in the mesiodistal and occlusogingival directions on tooth 21. There were mesial forces measured for all three materials at all activations, although the magnitudes were lower with TC-85 than with ATMOS or Zendura FLX. For example, with ATMOS and Zendura FLX at 0.25 mm lingual activation, there were 4.09 N and 3.32 N of extrusive force, respectively. However, at 0.50 mm activation, these force directions became intrusive. With TC-85, the occlusogingival forces were relatively minor, ranging from 0.06 to 0.10 N for both activations.

When tooth 21 was activated lingually, the right central incisor (tooth 11) also experienced a force in the lingual direction with all material types. When the activation was increased from 0.25 mm to 0.50 mm, the force level remained relatively constant with TC-85 (0.52 N to 0.51 N), whereas with ATMOS and Zendura FLX, the force level increased (2.01 N to 2.58 N, 1.59 N to 2.25 N, respectively). Extrusive forces were noted with all three materials at the different activations, and the force magnitudes were lowest with TC-85 (0.09–0.16 N) versus ATMOS (0.94–1.47 N) and Zendura FLX (0.28–0.63 N).

The effect of lingual activation on tooth 21 and the maxillary left central incisor (tooth 22) was different compared to its effect on tooth 11. Whereas ATMOS and Zendura FLX generated a mean lingual force, TC-85 generated a mean facial force. When the activation was increased from 0.25 mm to 0.50 mm, the force direction changed from lingual to facial for ATMOS (0.86 N to 0.54 N) and Zendura FLX (0.21 N to 0.41 N), whereas there was a slight increase in force magnitude with no change in direction for TC-85 (0.34 N to 0.51 N).

The force magnitude and direction were largely unpredictable, but some patterns were recognized based on tooth and material types. For instance, with TC-85, tooth 21 and 11 received forces in the lingual direction, whereas tooth 22 received forces in the facial direction. Both teeth 21 and 22 received mesial forces with all material types, but tooth 11 received distal forces with all material types.

### 3.2. Angular Deviation and Off-Axis Force

Table 8 provides a summary of the angular deviation and off-axis force magnitudes observed on tooth 21. TC-85 demonstrated the lowest angular deviation and off-axis force values for both 0.25 mm and 0.50 mm activations. Meanwhile, ATMOS and Zendura FLX

produced considerably larger angular deviations and off-axis force values, particularly at 0.50 mm activation.

**Table 8.** Angular deviation and off-axis force at the maxillary left central incisor (21) for each aligner material and activation amount.

| Activation (mm) | Material    | Angular Deviation (°) | Off-Axis Force (N) |
|-----------------|-------------|-----------------------|--------------------|
| 0.25            | ATMOS       | 47.3                  | 4.14               |
|                 | Zendura FLX | 66.3                  | 6.83               |
|                 | TC-85       | 33.2                  | 0.65               |
| 0.50            | ATMOS       | 68.2                  | 19.27              |
|                 | Zendura FLX | 60.2                  | 14.39              |
|                 | TC-85       | 12.0                  | 0.33               |

### 3.3. Moment-to-Force Ratios

The initial M/F ratios for the maxillary left central incisor are provided in Table 9. With 0.25 mm activation, the M/F ratios ranged  $-11.26$  mm to  $-11.93$  mm for TFM and  $-4.31$  mm for TC-85; based on the findings of Burstone and Pryputniewicz [19], these ratios indicate uncontrolled tipping. With 0.50 mm activation, the M/F ratio was  $8.61$  mm for ATMOS, indicating controlled tipping;  $4.84$  mm for Zendura FLX, controlled tipping; and  $-6.49$  mm for TC-85, uncontrolled tipping. None of the material types at any activation amount achieved total bodily movement, or a M/F ratio of  $10$  mm.

**Table 9.** Initial moment-to-force ratios generated on the maxillary left central incisor (21) for each aligner material and activation amount.

| Activation (mm) | Material    | M/F Ratio (mm) |
|-----------------|-------------|----------------|
| 0.25            | ATMOS       | $-11.93$       |
|                 | Zendura FLX | $-11.26$       |
|                 | TC-85       | $-4.31$        |
| 0.50            | ATMOS       | $8.61$         |
|                 | Zendura FLX | $4.84$         |
|                 | TC-85       | $-6.49$        |

## 4. Discussion

The biomechanics of clear aligner therapy is complex and not directly comparable to that of fixed appliance therapy. Unlike brackets and archwires, which have discrete points of force application, clear aligners depend on complex and dynamic contact points between the aligner and the dentition. Additionally, aligner design and material characteristics play important roles in determining the force systems generated during orthodontic tooth movement.

Direct printing of aligners allows for precise design and manufacturing, reducing errors associated with the conventional thermoforming method [14]. With DPA, the thickness is more uniform, and the offset between the aligner and dentition can be precisely controlled. This may contribute to improved fit and more predictable force systems [9–11]. Recently, a photopolymer resin called TC-85 has become available, with mechanical properties beneficial for CAT, including favorable strength, elasticity, and shape memory effect [14]. Therefore, the aim of the present study was to evaluate the forces and moments produced by DPA and TFM using ATMOS and Zendura FLX foils during lingual bodily movement.

#### 4.1. Forces and Moments from Planned Lingual Bodily Movement

In general, TC-85 exerted the lowest force and moment magnitudes for any given tooth and activation level compared to ATMOS or Zendura FLX. When the activation was increased from 0.25 mm to 0.50 mm, the force levels stayed relatively constant with TC-85, whereas with ATMOS and Zendura FLX, the force levels increased substantially. For example, on the maxillary left central incisor, the lingual force exerted by TC-85 with 0.25 mm activation was 0.99 N, within the range of optimal force for orthodontic tooth movement (0.50–1.00 N) [20]; with 0.50 mm activation, the force level increased by 65% to 1.53 N. With ATMOS and Zendura FLX, the lingual force levels with 0.25 mm activation were 3.82 N and 3.00 N, respectively, which increased by 2–2.7 times with 0.50 mm activation.

Based on these findings, 0.50 mm activation with conventional thermoplastic materials may not be recommended in the clinical setting due to the generation of excessively high force levels, which is associated with increased pain response and root resorption [20]. If greater activation is desired per stage, then DPA may induce a safer, more physiological force system. This finding is in agreement with another *in vitro* study comparing extrusion forces produced by clear aligners fabricated using TFM and DPA, which reported that the forces produced by TC-85 fell within ideal ranges, whereas the TFM group produced forces up to 20 times higher [11].

In CAT, it should be the goal of the clinician to design precise and accurate force systems that avoid unintended movement of teeth. Although the present study was planned for only the lingual bodily movement of the maxillary left central incisor, it was evident that a more complex system of forces and moments was produced on the tooth, such as unplanned mesiodistal and occlusogingival forces and crown angulation and rotational moments. For example, a 0.25 mm lingual activation using thermoformed aligners generated not only lingual forces but also extrusive forces of similar magnitudes. Interestingly, these extrusive forces were contrary to previous studies, which reported intrusive forces with the bodily movement of incisors [21,22]. When the lingual activation was increased to 0.50 mm, the vertical forces became intrusive, and the magnitudes of the intrusive forces were even greater than those of the lingual forces. On the other hand, the occlusogingival forces generated by TC-85 were minimal at both activation levels.

To quantitatively assess the directional control of the applied force system, angular deviation and off-axis force magnitudes were calculated at the maxillary left central incisor. TC-85 consistently delivered force vectors which were more closely aligned with the intended lingual direction at the center of resistance, with the smallest angular deviation and minimal off-axis force, particularly at the higher activation level. In contrast, thermoformed aligners produced larger directional deviations and greater off-axis loading. These findings suggest that TC-85 may provide a more predictable force system with fewer unwanted force components. Clinically, the minimization of unwanted forces means more accurate and efficient tooth movement, potentially reducing the need for redundant movements or additional aligner stages to correct side effects.

The observed lower and more consistent force application with DPA can be attributed to the unique thermo-mechanical properties of TC-85, particularly its elastic modulus and shape memory effect [14]. Compared to conventional thermoplastics such as PET-G or TPU, the lower elastic modulus of TC-85 allows for aligners with a lower force-deflection rate, generating less initial force for a given amount of activation and contributing to better adaptation to the dentition. Moreover, unlike conventional thermoplastics, which exhibit limited elastic recovery upon excessive activation, shape memory polymers like TC-85 are designed to actively return to a pre-determined shape upon thermal activation. This

characteristic can minimize permanent deformation and creep behavior, which can alter the intended aligner geometry and lead to inconsistent force application.

#### 4.2. Bodily Movement with Clear Aligners

Producing a force system conducive to bodily movement with clear aligners presents a significant biomechanical challenge, particularly in the absence of auxiliaries such as composite attachments or pressure points [21,22]. When an aligner is fitted onto a tooth to be displaced lingually, the aligner generates multiple contact points along the facial surface of the crown. This leads to a resultant lingual force and a moment of force at the tooth's center of resistance, causing the tooth to tip with the center of rotation near the center of resistance. This initial tipping movement induces elastic deformation of the aligner, forming new contact points which generate a moment of couple, counteracting the moment of force. The magnitude of this counter-moment depends on the aligner's precise fit with the tooth; if the fit is suboptimal due to a lack of retention, the counter-moment becomes insufficient, resulting in excessive crown movement relative to the root.

In the present study, none of the aligners generated a force system suitable for bodily movement of the maxillary left central incisor. This result was in accordance with previous *in vitro* studies [21,22], which found that effective control of incisor torque could not be accomplished using aligners when bodily movement was prescribed. Interestingly, in the present study, at 0.50 mm activation, ATMOS generated a mean M/F ratio of 8.61 mm, which is close to 10 mm, the M/F ratio for bodily movement [19]. This value also agrees closely with the mean M/F ratios determined by Gao and Wichelhaus [23] for 0.5 mm palatal tipping using Duran foils. However, this finding should be interpreted with caution, as the initial force and moment levels generated to achieve the M/F ratio were extremely high (7.70 N and 66.22 Nmm, respectively) and beyond the physiological range for safe tooth movement. Further studies are needed to determine the clinical conditions and aligner design features, such as composite attachments or pressure points, which may be required to reliably achieve bodily movement while maintaining optimal force levels.

#### 4.3. Effect on Adjacent Teeth

Unlike fixed appliances, clear aligners encompass the entire dentition, and the points of force application are difficult to determine. Additionally, the mechanical characteristics of the polymer influence the performance of the aligners. Thus, it is unclear how applying a force on a single tooth may transmit forces and moments across the entire arch. Kaur et al. [24] used a multi-tooth mechanical orthodontic simulator to evaluate the forces and moments produced by clear aligners on the maxillary arch during a 0.20 mm facial displacement. The group reported that for the maxillary right central incisor, the simulated displacement generated a facial force and a moment to tip the crown facially. On adjacent teeth, clinically relevant reciprocal forces and moments were present: lingual forces on both adjacent teeth, a moment to tip the crown lingually on the adjacent central incisor, and a clinically insignificant moment on the lateral incisor.

In the present study, when a lingual force was applied to the target tooth, the maxillary left central incisor, the adjacent maxillary central incisor also experienced forces in the lingual direction. When the activation on the target tooth was increased, a greater force magnitude was generated on the adjacent central incisor with thermoformed aligners, whereas the force magnitude stayed relatively constant with TC-85. The effect on the adjacent lateral incisor was more complex and dependent on material type and activation amount. With ATMOS and Zendura FLX, a 0.25 mm activation on tooth 21 resulted in lingual force experienced by the lateral incisor (0.86 N and 0.21 N, respectively). With TC-85, the reciprocal forces on the lateral incisor were in the facial direction at 0.25 mm

activation (0.34 N). When the activation was further increased to 0.50 mm, the force felt by the lateral incisor changed to opposite directions with ATMOS and Zendura FLX (0.54 N and 0.41 N, respectively). With TC-85, the increase in activation resulted in only a minor increase in force magnitude in the same direction.

In conventional biomechanics based on fixed appliance therapy, equilibrium dictates that a lingually directed force on the central incisor be balanced by facially directed forces on the adjacent teeth. The results from the present study indicate that this is not necessarily true with clear aligners. The contact geometry between the clear aligner and the dentition is complex and dynamic, and highly dependent on factors such as material properties and planned tooth movements. In general, the unpredictable forces and moments measured on the target tooth and the adjacent teeth in the present study highlight the complexity of the biomechanics of clear aligner therapy and may help explain the ongoing challenges in achieving predictable clinical outcomes with this treatment modality.

#### 4.4. Limitations

This study was an *in vitro* investigation of clear aligner biomechanics. Thus, forces and moments measured by the experimental apparatus cannot completely predict the behavior of clear aligners *in vivo*. There are several limitations to the experimental setup. Firstly, the periodontal ligament was not simulated. The elastic fixture of teeth to the bone imparts a viscoelastic property to the periodontal ligament, allowing for time-dependent elastic compression [25]. The forces and moments measured in this study were greater than what is recommended in the literature and may be partly explained by the lack of the periodontal ligament in the experimental apparatus. Secondly, the effect of masticatory forces was not simulated. The occlusal forces generated during swallowing may exert clinically significant intrusive forces [26]. Thirdly, the presence of saliva was not reproduced. Saliva alters the mechanical properties of clear aligners by water absorption, and hygroscopic expansion of thermoplastic materials has been previously reported [27].

## 5. Conclusions

When lingual bodily movement was prescribed to the maxillary left central incisor, lingual force was generated, but unplanned forces and moments also occurred in the mesiodistal and occlusogingival directions. Reciprocal forces and moments were observed on the adjacent teeth. DPA made from TC-85 resin produced lower, more physiologically compatible force levels and more predictable force systems than thermoformed aligners from ATMOS (PET-G) and Zendura FLX (TPU) foils. A force system conducive to bodily movement could not be achieved with any of the tested materials. Clinicians may consider adopting DPA with materials like TC-85 for more efficient treatment planning with larger activation per aligner, minimizing side effects, and potentially reducing the number of aligners. Auxiliaries such as composite attachments or pressure points may still be necessary for challenging tooth movements.

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