

Effect of trimming line design and edge extension of orthodontic aligners on force transmission: An in vitro study

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ABSTRACT

Objectives: To investigate how the stress distribution and forces transmitted from orthodontic aligners to the tooth surface are affected by the geometry and extension of the trimming line.

Materials and methods: Thirty-six aligners were thermoformed from Zendura FLX sheets (0.75 mm thick) and divided into four groups based on the design of the trimming line: Scalloped, Scalloped extended, Straight and Straight extended. Fuji pressure-sensitive films were used for pressure measurement. The pressurized films were scanned and evaluated. Pressures and forces were measured over the entire facial surface of an upper right central incisor (Tooth 11) and at 7 different locations [cervical, middle, incisal, mesio-incisal, mesio-cervical, disto-incisal, and disto-cervical]. In addition, the thickness of the aligners at these 7 sites was measured with a digital caliper.

Results: The active force ranged from (2.2 to 6.9) N, and the average pressure was (1.6–2.7) MPa. The highest values were recorded for the (straight extended) design, while the lowest values were recorded for the scalloped design. The forces and stresses were not uniformly distributed over the surface. When the values in each area were compared separately, significant differences were found between the different designs in the cervical area, with the scalloped design transmitting the lowest cervical forces. Aligner thickness was drastically reduced (60–75% thinning) over the entire tooth surface after thermoforming.

Conclusions: The straight extended design of aligner's trimming line exhibited more uniform force transfer and stress distribution across the surface than the other designs.

Clinical Relevance: The trimming line design could have a significant impact on the clinical outcome of orthodontic aligner treatment.

1. Introduction

In the era of aesthetic dentistry, clear aligners are widely used due to their transparency, as well as their comfort and acceptance by patients, compared to fixed orthodontic braces [1]. Moreover, they are clinically and technically easier to be handled by dentists and patients. In addition, they need shorter chair-time and fewer dental appointments than fixed appliances [2,3]. Thanks to the simple oral hygiene measurements, patients with clear aligners can also maintain or even improve their periodontal health [4,5]. Orthodontic treatment with aligners is based on gradual movement of the teeth using a series of custom-made plastic splints, each of which can progressively move the targeted teeth by small

amounts over a period of 10 to 14 days, approximately 0.2 mm for translations and 3° for rotations. Ideally, aligners should be worn the whole day, and removed only for eating, and teeth brushing [6,7].

In comparison with fixed braces, the force systems of aligners are more complex, as there are no specific, known points for force application and multiple parameters are used to determine the treatment outcome [8]. The biomechanical characteristics of aligners are influenced by aligner thickness [9,10], aligner extension [11], material properties [12,13], amount of activation [14,15], and attachments use [16]. Force transmission by aligners differs in that the geometry of the splint defines the amount and direction of tooth movement [17]. There is a pre-defined geometrical mismatch between the aligner splint and the

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crown of the treated tooth, which generates 3-dimensional force systems distributed over the entire contact area between the tooth and the aligner [18,19].

To achieve optimal outcomes of the aligner treatment, numerous studies have been conducted to evaluate the biomechanical characteristics of the aligners, either numerically using finite element methods [19–22], or experimentally using strain gauge sensors [23,24], pressure sensitive films [25,26], specialized sensors [15,27,28], along with different customized multi-axis force/torque biomechanical systems [6, 29–31]. However, there is not yet a clear demonstration of the biomechanical system of aligners.

One of the factors that can influence the biomechanical behavior of the aligner is the design of the trimming line [11,32]. In this context, the aim of our current experiment is to study, using pressure-sensitive films, the distribution map of the contact pressure generated by the aligner on the tooth surface, and to understand how force levels, stress generation and stress distribution are affected by the geometry and extension of the trimming line of the aligner.

2. Materials and methods

2.1. Design of digital models and 3D printing

The upper right central incisor (Tooth 11) was selected as the treated tooth in the present study, because it has the flattest facial surface and is therefore suitable for the experiment. Additionally, most of the experimental reports refer to forces acting on the maxillary central incisor, so our results can be compared with those published in the literature.

At the beginning of the modeling, a digital model of an upper jaw was created from a three-dimensional data set of a maxilla with all 16 teeth (Digimation Corp., St Rose, Louisiana, USA). The digital model was imported as an STL file into an image processing and editing software (Mimics Innovation Suite, Mimics 24.0 / 3-matic 16.0; Materialise, Leuven, Belgium). In 3-matic software, three digital models were designed for different purposes in the study (Table 1). The first model (1st Model) is an aligned model, with no tooth misalignments and with no housing space for the pressure-sensitive film. The second model (2nd Model) is also an aligned model, but with a housing space around the four anterior incisors and their corresponding gingival area (Fig. 1). This housing space was designed to eliminate the effects of the thickness of the pressure-sensitive film on the measurements and to make the results more realistic. The housing space was designed by digitally subtracting 100 µm from the targeted area using the solid uniform offset tool in 3-matic. In the third model (3rd Model), tooth 11 was bodily-translated 0.2 mm towards the facial direction, then a housing space was designed. The three digital models were exported as STL files to a 3D-printer (P20+; Straumann, Basel, Switzerland) and printed using a resin (P pro resin; Straumann, Basel, Switzerland).

2.2. Thermoforming and trimming of the aligners

To investigate the effects of trimming line design, 36 aligners were thermoformed from thermoplastic sheets (Zendura FLX; Bay Materials LLC, Fremont, CA, USA) with a thickness of 0.75 mm. The 1st 3D-printed model, printed out of the 1st digital model, was used for thermoforming the aligner sheets. Thermoforming was carried out according to the manufacturer's guidelines (220 °C, 4.8 bar, 40 s) with a thermoforming device (Biostar; SCHEU-DENTAL GmbH, Iserlohn, Germany), which is

functioning with positive pressure to allow better adaptation of the aligner to the 3D-printed model. The 36 aligners were divided into 4 groups, nine aligners per group ($n=9$), according to the design of the trimming line (Fig. 2): Scalloped trimming following the gingival line of each tooth (Scalloped); Scalloped trimming extended 2 mm beneath the gingival line (Scalloped Extended); Straight trimming at the level of the gingival line (Straight); and Straight trimming extended 2 mm beneath the gingival line (Straight Extended). Thermoforming and trimming of the aligners were done by a trained technician, in order to standardize the trimming line design of each group.

2.3. Method of measuring pressure with pressure sensitive films

2.3.1. Types of pressure sensitive films

Pressure sensitive films (Fuji Prescale Film; Fuji Film, Tokyo, Japan) were used for pressure measuring. These films are provided either in mono-sheet type or two-sheet-types. Both types are available in different sensitivity levels, each with a specific effective range. In the current study, we used the two-sheet type films, which are typically supplied in A-transfer sheet and C-developer sheet, whose combined thickness was specified by the manufacturer to be about 100 µm. The A-film contains microcapsules manufactured to rupture and react with an active layer of developing material on the C-film depending on the pressure applied, so that the optical density response corresponds to the pressure intensity and is expressed as a change in color intensity from pale pink to dark red [33].

In the present study, the super low pressure (LLW) film, whose sensitivity range is 0.5–2.5 MPa, was used for measuring the passive pressure resulting from the passive contact between the aligner and the 2nd printed model (aligned model). The low pressure (LW) film, whose sensitivity range is 2.5–10.0 MPa, was used for measuring the active pressure resulting from active contact between the aligner and the 3rd printed model (malaligned model).

2.3.2. Steps of pressure recording

In the test phase, parts of the two pressure foils were cut to fit into the housing space designed for them in the 2nd and the 3rd printed models (Figs. 3 and 4). They were then inserted carefully between the aligner and the printed model avoiding the application of any unwanted compressive or shear stress. For each individual aligner, both passive and active pressures were measured (Fig. 4). For each measurement, the pressure film was held at the designated location between the aligner and the printed model for 2 minutes in order to measure the continuous pressure, not just the momentary pressure (pressure film manufacturer's guidelines). All measurements were carried out by a single, well-trained operator on the same 3D-printed models.

2.3.3. Scanning of the pressurized films and extraction of data

The pressurized film of each measurement was scanned using a scanner (EPSON perfection V300 series; SEIKO Epson CORPORATION, Japan) which has a maximum resolution of 12,800 dpi. The scanning resolution was set at 0.125 (200 dpi). The pressure distribution recorded by each film has been analyzed, digitalized, and quantified using the software FPD-8010E analysis system (Fuji Film, Tokyo, Japan). With the help of the scan analysis software, the average pressure (MPa) and the force (N) over the entire facial surface of the tooth and at 7 different locations [Cervical (C), Middle (M), Incisal (I), Mesio-Incisor (MI), Mesio-Cervical (MC), Disto-Incisor (DI), and Disto-Cervical (DC)] of the

Table 1

Table of different digital Models used in the current study, their description and the use of the corresponding 3D-printed models.

Model	Description	Purpose
1 st Model	An aligned model without any malposition of the teeth and without any housing space for the pressure film.	Thermoforming
2 nd Model	An aligned model with a created housing space around the four anterior incisors and the corresponding gingival area.	Measurement of the Passive Pressure
3 rd Model	The tooth 11 was translated 0.2 mm bodily to the facial direction, then a housing space was created.	Measurement of the Active Pressure



Fig. 1. Digital Model of an upper dental arch with a 100 µm deep space at the four anterior teeth region for housing of the pressure sensitive film (Right), corresponding 3D-printed model (Left).

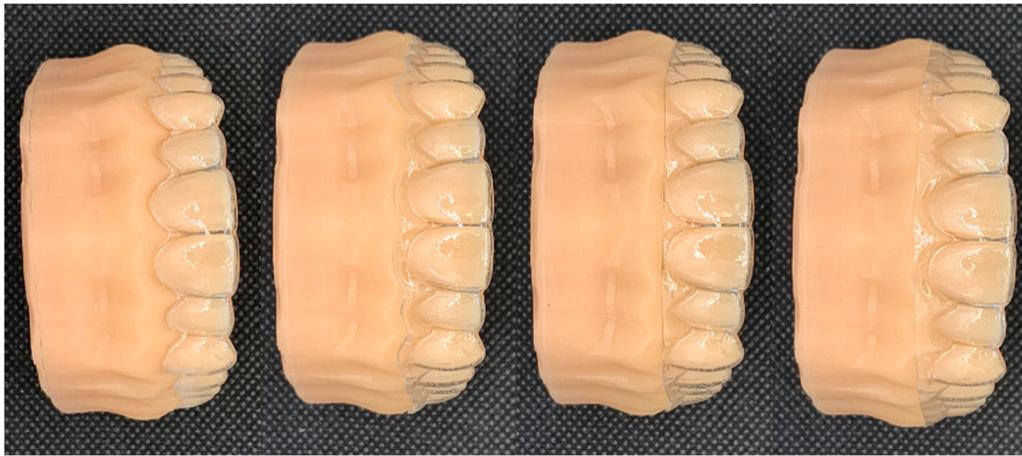


Fig. 2. Different designs of trimming line of orthodontic aligners; from Left to Right: Scalloped, Scalloped Extended (2 mm), Straight, and Straight Extended (2 mm).



Fig. 3. Pressurized Fuji Prescale pressure sensitive film used for investigating the stress distribution map generated by clear aligner on the surface of a 0.2 mm facially malaligned upper right central incisor (Tooth 11) of a 3D-printed model.

facial surface of tooth 11 were defined and recorded (Fig. 5).

2.3.4. Calibration and standardization steps

Prior to scanning, the scanner was calibrated using a special calibration sheet supplied by the manufacturer. The type of scanned pressurized film was selected in the software, either LW or LLW. Additionally, the room temperature and the relative humidity were observed throughout the test procedure and measured with a digital meter (Technoline WS 9440 Indoor climate station; Technotrade GmbH, Wildau, Germany). The values of the temperature and the relative humidity were entered into the software to be included in the measurement

and calculation process, since microcapsule rupture, subsequent reaction with the developing film, and final color density depend on both temperature and humidity. The temperature was measured in the range of 21 ± 2 °C, and the relative humidity was in the range of 29 ± 4 %. During scanning, the lustrous side of the pressurized A-Transfer sheet was fit into the scanner facing down, while the rough side (active color generation side) was facing up (manufacturer's instructions).

In order to exclude the factor of the lag time between the testing step and the scanning step of the pressurized film, a sensitivity analysis was performed by scanning the same pressurized films at 3 different times over a period of one hour (immediate scanning, after 30 minutes, and

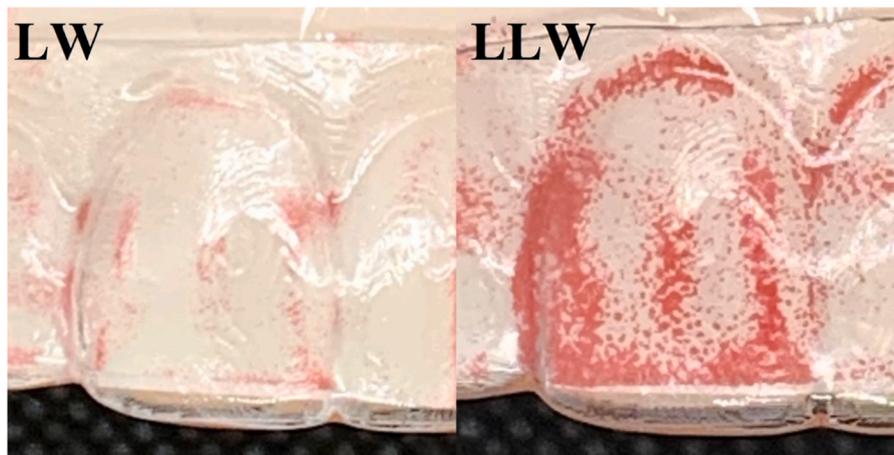


Fig. 4. Pressurized Fuji Prescale pressure sensitive film with different sensitivity used for investigating the stress distribution map generated by clear aligner; Low Pressure (LW) film for measuring the active pressure and Super Low Pressure (LLW) film for measuring the passive pressure.

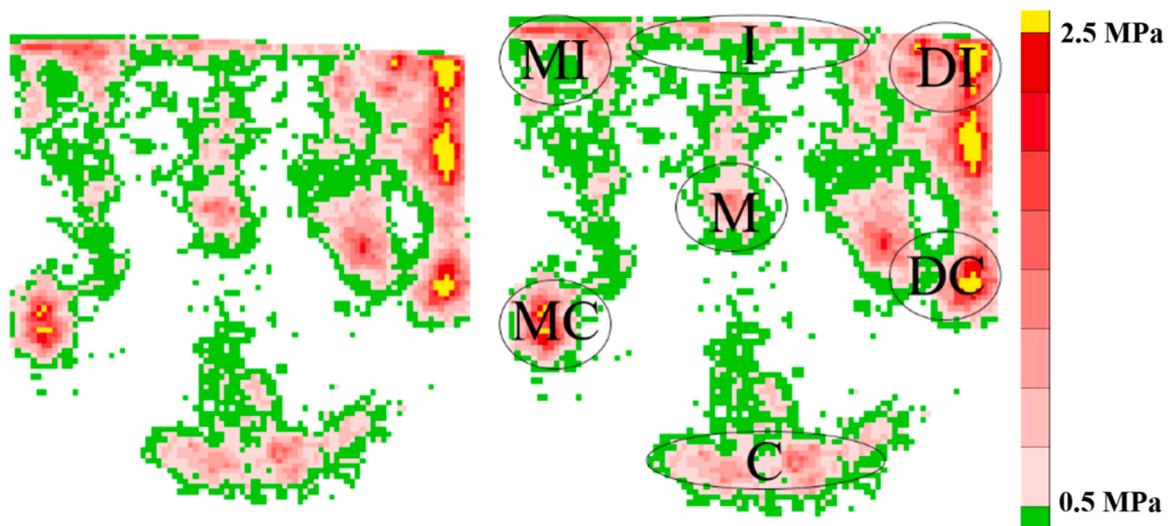


Fig. 5. A scan of a pressurized Fuji Prescale pressure sensitive film showing stress distribution map generated by a clear aligner over a 0.2 mm facially malaligned upper central incisor tooth (Tooth 11). Pressures and forces were measured by a special software at 7 different pre-defined areas; Cervical (C), Middle (M), Incisal (I), Mesio-Incisal (MI), Mesio-Cervical (MC), Disto-Incisal (DI), and Disto-Cervical (DC).

after an hour). With LLW and LW films, we found no difference in the recorded pressure values between the different scanning times, when all other factors were set fixed.

During aligner insertion, passive forces occur by default due to the good fit between the thermoformed aligner and the printed model, in addition to the undesirable forces generated during aligner insertion. Hence, care was taken at all times during the experiment to ensure that no unwanted pressure was applied to the films, especially during the insertion and removal of the pressure films. Also, the passive pressure generated by each aligner was subtracted from the active pressure generated by it, at each predetermined area, to get the real pressure (corrected values), generated due to the difference in the trimming line design. The active, the passive and the corrected values of the resulted pressures and forces were statistically analyzed.

2.4. Measurements of aligner thickness

Additionally, to study the variation of aligner thickness after thermoforming over the tooth, we have used a digital caliper (Dial Caliper D, AURA-DENTAL GmbH, Aura an der Saale, Germany) to measure the differential thickness at the center of the 7 previously mentioned areas

(C, M, I, MI, MC, DI, and DC).

2.5. Statistical analysis

Numerical data were presented as mean and standard deviation (SD) values. They were explored for normality by checking the data distribution and using Shapiro-Wilk test. Data showed non-parametric distribution, so they were analyzed using Kruskal-Wallis test followed by Dunn's post hoc test with Bonferroni correction. The significance level was set at $p \leq 0.05$. Statistical analysis was performed with R statistical analysis software version 4.1.3 for Windows (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

For each aligner individually and with a thorough evaluation of the forces and stress distribution over the surface, we found that the forces and stresses are not evenly distributed over the entire facial tooth surface. The stresses are concentrated mainly in 7 areas of the facial surface of the tooth 11; Cervical (C), Middle (M), Incisal (I), Mesio-Incisal (MI), Mesio-Cervical (MC), Disto-Incisal (DI), and Disto-Cervical (DC) (Fig. 5).

There is a significant difference between each area of interest, the stresses and forces are highest at the incisal third of the tooth. The scan of the pressurized film was superimposed over the digital model to better visualize the stress distribution areas over tooth 11 (Fig. 6).

After scanning and measuring the stress values, significant differences are shown between the four different trimming designs (Figs. 6 and 7, Tables 2 and 3). The measured values of the mean active forces applied over the entire tooth surface were in the range of (2.2–6.9) N, the mean active pressure was in the range of (1.6–2.7) MPa, while the passive pressure was in the range of (0.3–1.3) MPa. The highest values of active force, active pressure, and passive pressure were recorded for the straight extended trimming design, and the lowest values were recorded for the scalloped design. On the other hand, there was no significant difference in corrected pressure values of the four different trimming designs (Fig. 7, Table 2). When comparing the different trimming designs, the difference in active force was significant at the cervical area including Cervical (C), Disto-Cervical (DC), and Mesio-Cervical (MC), with the scalloped design having the lowest values (Fig. 7, Table 3).

The thickness of the aligner (0.75 mm) is drastically reduced to (0.2–0.3) mm (60–75% thinning) on the entire tooth surface after deep drawing, while it is less reduced (about 0.6 mm) (20% thinning) at the incisal edge, with no significant difference between different trimming line designs (Fig. 8).

4. Discussion

Research into aligner design and material properties provides necessary information to address some of the drawbacks and limitations of aligners. Therefore, in this article, we have attempted to understand the effect of aligner trimming design and edge extension on force transmission and stress distribution using pressure-sensitive films. To our knowledge, these pressure-sensitive films have been used for the investigation of orthodontic aligners in only two studies: an in-vivo study by Barbagallo et al. [26] and another in-vitro study by Cervinara et al. [25]. Our research group sought to apply this technique to further investigate the biomechanics of aligners.

Biomechanical tooth movement is dependent on several factors. One is the resulting force, which in turn depends on its point of application, magnitude, and direction, and the other is the center of resistance of the tooth [34]. For example, to achieve a bodily tooth movement in a specific direction, the force vector should pass through the center of resistance of the targeted tooth. This is not directly achievable clinically because the center of resistance of the bone-anchored tooth is located somewhere in the root [35]. In the fixed braces system, it is possible to indirectly create a bodily tooth movement using some biomechanical approaches, involving for instance the use of wires with square section designed to apply a force couple opposite to the moment of the force around the center of resistance [34]. In contrast, in the aligner system, it is much more difficult to apply the same biomechanical techniques

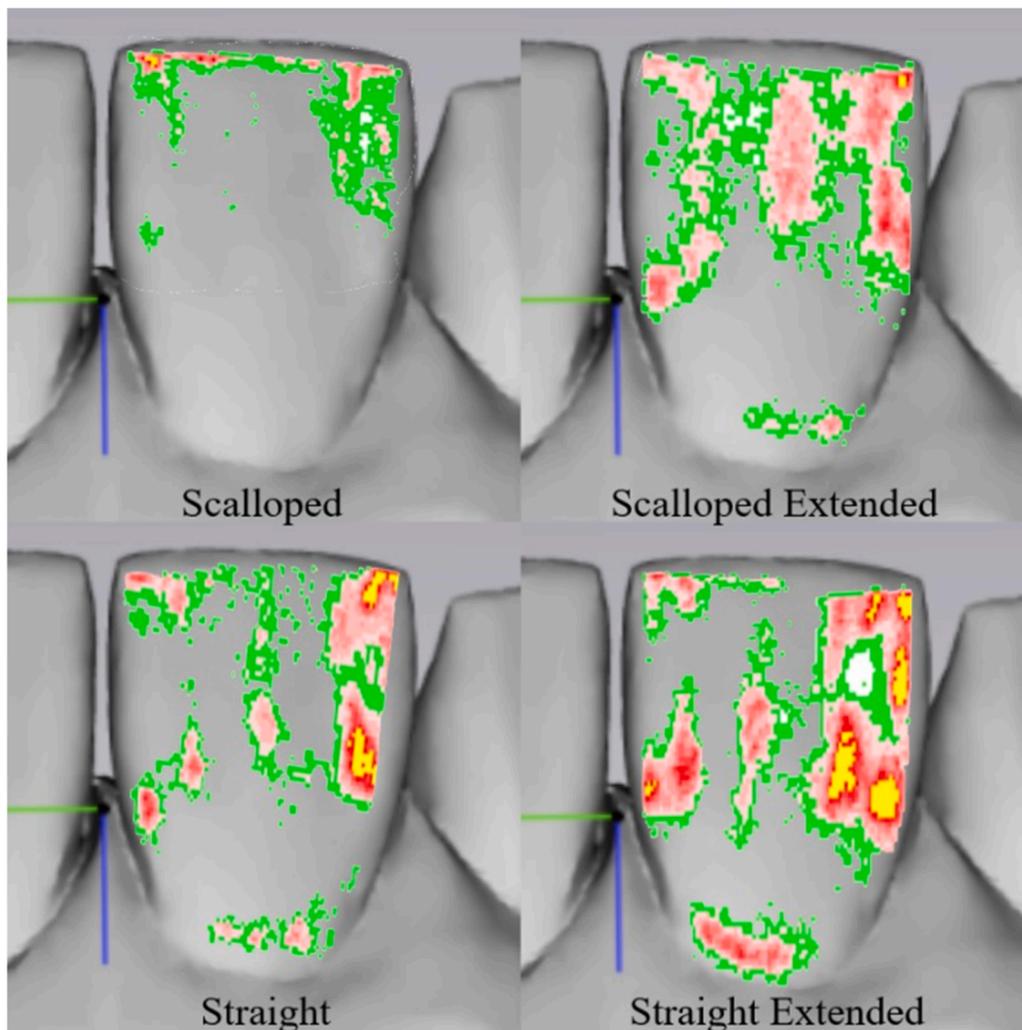


Fig. 6. A representative superimposition of the scan of a pressurized Fuji pressure sensitive film over the digital model for better understanding of the stress distribution areas over the upper right central incisor using different trimming line design; scalloped, scalloped extended, straight, straight extended.

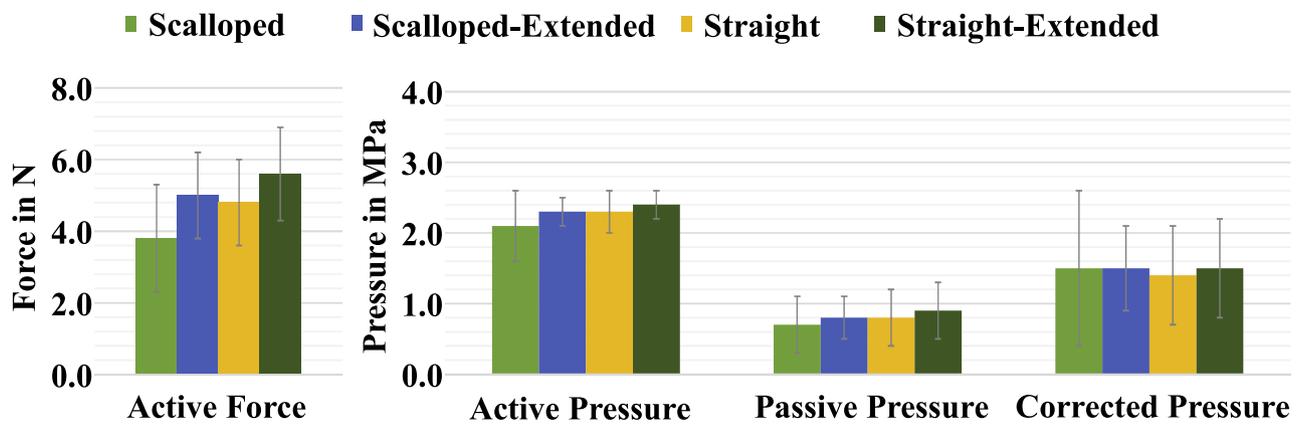


Fig. 7. Mean active force (in N), and mean active, passive, and corrected pressure (in MPa) exerted across the entire surface of tooth 11 by different trimming design of an orthodontic aligner.

Table 2

Mean active force (in N), and mean active, passive, and corrected pressure (in MPa) exerted across the entire surface of tooth 11 by different trimming design of an orthodontic aligner.

	Scalloped	Scalloped Extended	Straight	Straight Extended	p-value
Active Force (N)	3.8±1.5 ^B	5.0±1.2 ^{AB}	4.8 ±1.2 ^{AB}	5.6±1.3 ^A	0.010 *
Active Pressure (MPa)	2.1±0.5 ^B	2.3±0.2 ^{AB}	2.3 ±0.3 ^{AB}	2.4±0.2 ^A	0.010 *
Passive Pressure (MPa)	0.7±0.4 ^B	0.8±0.3 ^B	0.8 ±0.4 ^{AB}	0.9±0.4 ^A	0.001 *
Corrected Pressure (MPa)	1.5±1.1 ^A	1.5±0.6 ^A	1.4 ±0.7 ^A	1.5±0.7 ^A	0.238

Different superscript letters indicate a statistically significant difference within the same horizontal row

* significant ($p < 0.05$).

Table 3

Active Forces (in N) generated from different trimming design of an orthodontic aligner at 7 different areas of the facial surface of tooth 11; Cervical (C), Middle (M), Incisal (I), Disto-incisal (DI), Disto-cervical (DC), Mesio-incisal (MI), and Mesio-cervical (MC).

Point	Force (active) (N) (Mean±SD)		Straight	Straight Extended	p-value
	Scalloped	Scalloped Extended			
C	0.2±0.4 ^B	2.1±1.2 ^A	0.8±0.7 ^B	2.0±1.1 ^A	<0.001 *
M	0.1±0.3 ^B	1.2±1.0 ^B	1.1±1.1 ^B	3.2±1.5 ^A	<0.001 *
I	5.3±3.2 ^A	4.4±1.6 ^A	3.6±1.7 ^A	4.6±2.0 ^A	0.423
DI	8.0±3.8 ^A	8.0±2.8 ^A	8.2±3.0 ^A	8.2±3.4 ^A	0.998
DC	4.2±2.9 ^C	8.2±3.0 ^{AB}	5.6 ±2.7 ^{BC}	9.4±2.2 ^A	<0.001 *
MI	7.3±3.4 ^A	6.1±1.6 ^A	5.2±2.1 ^A	5.1±1.4 ^A	0.155
MC	1.0±0.5 ^B	5.0±2.6 ^A	4.8±1.9 ^A	6.7±2.1 ^A	<0.001 *

Different superscript letters indicate a statistically significant difference within the same horizontal row

* significant ($p < 0.05$).

because the forces vary from the incisal to the gingival region and the mode of action of the aligner is based on a geometrical mismatch between tooth and aligner, and hence stresses are transferred to a wider and less defined contact area [18–20]. Therefore, the predictability of

bodily movement in clear aligner treatment is generally limited, as recently noted in a comprehensive systematic review [36].

Although orthodontic aligners move teeth by pushing rather than pulling - which should allow intimate contact between the aligner and tooth surface facilitating even stress distribution and better force transmission [18] -, the uneven topography of the tooth surface plays a major role in the stress distribution resulting in uneven distribution of stress over the tooth surface. In agreement with Barone et al. [19] and Cervinara et al. [25], our study showed that the contact of the aligner with the tooth surface is not homogenous, there are areas of relief and others with intimate contact, and hence the force level differs from point to point all over the surface. The stress concentration areas recorded in the present experiment are similar somehow to those reported by Cervinara et al. [25]. In the current study, we have initiated a facial bodily translation of tooth 11. In order to create a bodily translation (the crown and the root apex move the same distance in the same horizontal direction), the aligner must conduct forces both at the incisal edge and at the gingival crevice, where the force at the gingival margin must exceed the force at the incisal edge due to the location of the force with respect to the center of resistance, otherwise a tipping movement will occur [34, 37,38]. As shown in the results, none of the aligners tested could achieve that, but at least with the (straight extended) design, the difference between the forces transmitted to the cervical area was significantly higher, and so the difference between the incisal forces and the cervical forces is smaller, and the tooth then has more probability to move bodily than in tipping pattern.

Trimming of the aligner in a scalloped form is mainly done to improve the aesthetic appearance of the aligner by following the natural gingival margins. However, this involves an unavoidable polishing step, which might lead to weakening of the material and excessive flexibility of the margins. As a result, the aligner gripping of the tooth is poorer and the force cervically is reduced [38]. However, in the case of straight trimming, the polishing step could be considerably minimized. Additionally, with the extension of the margins, the grip and the control become better [11,32].

The initial forces and stresses measured in this study are within the range of values reported in the literature. Cervinara et al. [25] reported that the maximum passive pressure recorded was 1.5±0.5 MPa, which is well-matched with our results (max. 1.3 MPa). The mean active pressure of 2.65 MPa calculated by Cervinara was also consistent with our results. Active force measurements were as well in the range of (2.2–6.9) N, which is corresponding to reports by Elkholy et al. (2.3–10.2 N) [12,39] and Hahn et al. (3.9–5.4 N) [10,40], who used customized biomechanical measuring systems on upper central incisors. Likewise, Xiaowei et al. [15] reported force levels at (7.7 N) using a micro-stress sensor system. Similarly, Xiang et al. [28] reported force values around 8.0 N using a thin-film pressure sensor. The slight difference between the

THICKNESS OF THE ALIGNER AT FACIAL PART OF TOOTH 11

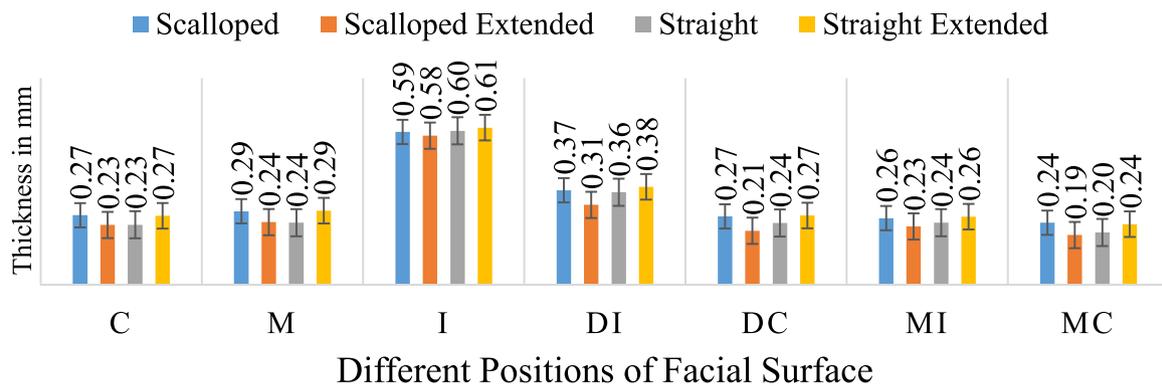


Fig. 8. Varying thickness (in mm) of different trimming designs of aligners after thermoforming at 7 different areas at the facial surface of tooth 11; Cervical (C), Middle (M), Incisal (I), Disto-Incisal (DI), Disto-Cervical (DC), Mesio-Incisal (MI), and Mesio-Cervical (MC).

values can be attributed to the variation in the experimental set-up and the used aligner material.

Nevertheless, for a bodily movement of upper central incisor, the recorded forces are higher than the ideal orthodontic forces (0.7–1.3 N) [41,42]. Higher forces are expected and accepted in in-vitro studies because neither PDL nor bone are present in the experimental setups. Moreover, only the horizontal force components are involved in the tooth facio-lingual bodily movement, however, using the pressure sheet, we could measure the normal forces applied on the surface which include also the vertical component of the force added to the total force values. Additionally, the initial high force levels generated by aligners drop within the first 24 h of use, due to wear and fatigue [23].

A well-fit well-retained aligner is expected to transmit higher forces and achieve a more accurate tooth movement [11]. The passive forces, generated from the inherent contact between the passive aligner and the 3D-printed model, could be an indicator of the engagement and the retention of the aligner. In agreement with Cowley et al. [11,37], the straight extended design showed the highest passive force, followed by the straight design, while the scalloped designs transmit the lowest forces. Also, Gao et al. [32] reported that the forces generated by the aligner vary depending on the width of the aligner the trimming design and extension, with non-extended aligners generating significantly lower forces than those with extension.

Although the thickness of the aligner plays an important biomechanical role [32], the irregular thickness of an aligner and the material thinning during deep drawing make it difficult to predict the treatment outcomes [43]. It has been reported that the thickness variation of a thermoplastic material alters the force-deformation properties, with a reduction in thickness decreasing the stiffness and diminishing the transmitted force [10,32]. Also, decreasing the thickness will increase local and bodily aligner deformation, and hence decrease tooth to aligner contact areas [37]. In agreement with Jones et al. [44] and Lee et al. [43], we noted that the thermoforming process drapes over the model leading to a drastic thinning of the material (60–75%), especially in the middle and gingival regions, and less thinning at the incisal edge (around 20%). This reduction in thickness results in increased flexibility allowing for easier deformation, and increased risk of fracture. Therefore, in order to obtain a desired and predictable outcome, aligner thickness and material properties should be adjusted over the course of treatment [37]. The use of 3D-printed aligners is proposed as an attempt to obtain a homogeneous thickness over the entire surface.

The limitations of the current study might be due to some factors, such as the exclusive choice of buccal translation as a test movement and the choice of a simulated single-tooth discrepancy (with a simplified

force system as a result). Also, pressure sensitive films were developed for direct measurement of the pressure between two surfaces, and as a trial to overcome the bulky thickness of other pressure sensors. Although this technique is rapid, straight forward, and completely dry, it is very sensitive. It is also dependent on temperature, humidity, and load-rate. As well, Fuji suggests that stain density changes with time, therefore all stains should be recorded at a fixed time after application of pressure [45–47]. Furthermore, in our in-vitro study, in spite of designing a housing space to exclude the pressure generated by the thickness of the pressure films (100 μm), unavoidable additional pressure was to be expected, especially during insertion and extraction of the aligner, particularly in undercuts. In addition, the periodontal ligament and bone were not taken into account, so higher forces were to be expected. In addition, there are normal variations and geometric inaccuracies that occur during the thermoforming process [32,43], therefore, we tried to control the process and standardize every step, and use a larger sample size (nine aligners per group). Finally, the experimental conditions did not allow for a realistic simulation of the intraoral environment in terms of temperature and humidity, which have significant effect on the mechanical properties of the aligner materials. Colder and drier conditions contribute to the generation of higher forces than in the intraoral environment.

Zendura FLX, which was used in the current study, is a multi-hybrid material developed to overcome the limitations of a single-layer material and to improve the physical properties of maximum tensile load-bearing capacity [43]. Further studies will test other materials using the same technique to investigate the factor of material type. Also, the finite element method will be a useful tool to better understand the effects of the trim line design. In addition, the effect of aligner margin expansion on periodontal and gingival health should be investigated.

5. Conclusions

- 1 During bodily movement of the upper central incisor by an orthodontic aligner, the stress is not evenly distributed over the tooth surface but concentrates at specific areas which could be considered as the force application areas.
- 2 Scalloped trimming leads to higher flexibility and material weakening at the marginal areas, which results in reduction of the amount of force applied on the tooth near the gingival area, decreasing the probability of accomplishing more complex movements (such as bodily translation).

- 3 Trimming of the aligner in (straight extended) design is a way to increase stiffness, retention, and gingival adaptation of the aligner, and consequently to achieve better stress distribution and better control of tooth movement, and apply more force at the gingival area, closer to the center of resistance, thus potentially improve control of bodily movement.
- 4 Thermoforming of aligner sheets is accompanied by a great reduction of the thickness (about 60–75% thinning), especially at the gingival and the middle area, which affects the generated force levels and the stress distribution.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

Ethical Approval

Not Applicable.

Informed Consent

Not Applicable.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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