ORIGINAL ARTICLE

Computer-aided finite element model for biomechanical analysis of orthodontic aligners

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Abstract

Objectives To design a finite element (FE) model that might facilitate understanding of the complex mechanical behavior of orthodontic aligners. The designed model was validated by comparing the generated forces — during 0.2-mm facio-lingual translation of upper left central incisor (Tooth 21) — with the values reported by experimental studies in literature.

Materials and methods A 3D digital model, obtained from scanning of a typodont of upper jaw, was imported into 3-matic software for designing of aligners with different thicknesses: 0.4, 0.5, 0.6, 0.7 mm. The model was exported to Marc/Mentat FE software. Suitable parameters for FE simulation were selected after a series of sensitivity analyses. Different element classes of the model and different rigidity values of the aligner were also investigated.

Results The resultant maximum forces generated on facio-lingual translation of Tooth 21 were within the range of 1.3–18.3 N. The force was direction-dependent, where lingual translation transmitted higher forces than facial translation. The force increases with increasing the thickness of the aligner, but not linearly. We found that the generated forces were almost directly proportional to the rigidity of the aligner. The contact normal stress map showed an uneven but almost repeatable distribution of stresses all over the facial surface and concentration of stresses at specific points.

Conclusions A validated FE model could reveal a lot about mechanical behavior of orthodontic aligners.

Clinical relevance Understanding the force systems of clear aligner by means of FE will facilitate better treatment planning and getting optimal outcomes.

Keywords Biomechanics · Orthodontic force · FEM · Tooth movement · Thermoplastic stent · Removable dental appliances

Highlights

- Experimental biomechanical studies of aligners have many limitations.
- Finite element method might help for better understanding of force transmission by aligners.
- The deformation of the aligner is a combination of bending and stretching.
- The generated forces are almost directly proportional to the rigidity of the aligner.

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Introduction

Clear aligners are a series of removable plastic stents, which are customized for each orthodontic patient to effectively move teeth into their desired aligned position. They have a high esthetical appearance because of being transparent

and almost invisible. Besides, they are more comfortable and easier to keep a good oral hygiene, compared to fixed orthodontic braces [1–3]. In addition, clinically and technical-wise, they are much easier to be handled in every-day practice than fixed appliances. Also, they need shorter dental appointments and seem to be ideal for retreatment cases [4, 5]. As well, they may be used for improvement of some bad parafunctional habits during treatment, such as bruxism, and may also be beneficial for treatment of temporomandibular joint problems [6, 7].

Formerly, treatment planning for aligners was accomplished on plaster models at a millimeter scale. Recently, and with the revolution of digital scanning, CAD-CAM technologies, and 3D–printing, digital treatment planning is applied for more accurate outcomes at the scale of hundredths of millimeter [8]. However, for a better treatment planning and to get optimal outcomes, a very good understanding of mechanical behavior of the aligners should be available. To our best knowledge, and despite several investigations of clear aligners in many aspects, still, there is lack of data in the literature about the biomechanical behavior of orthodontic aligners [9, 10].

Tooth movement by aligners is based on a limited programmed deviation between the setup position and the position of the targeted real tooth. The geometry of the aligner's tray defines the amount of movement [11]. In most popular aligner systems, each single aligner of the treatment series is designed to move the targeted tooth by around 0.2 mm for translations and about 3° for rotations in a period of approximately 10–14 days [3, 12, 13].

Many methods were used for biomechanical analysis of aligners, such as strain gauge [14, 15], pressure sensors [16–18], pressure sensitive films [19, 20], and different customized biomechanical systems [3, 21–23]. However, all applied techniques have shortcomings and limitations and showed discrepancies of the reported results [3, 19, 20, 24]. Hence, as a promising alternative approach, using the finite element method (FEM) might lead to a better understanding of the behavior of the orthodontic aligners, through a mechanical numerical stress/strain analysis validated by standardized experimental setups, as well as well-controlled clinical studies [24].

From the time of the 70 s of the last century, FEM has been a widely used tool to evaluate the effectiveness of dental appliances [25]. It is a modern engineering tool for structural analysis that is applicable to bodies of irregular geometries and heterogeneous material properties. The structure is divided into finite number of elements connected by nodes. By choosing a suitable mesh and an appropriate mathematical model for each element, the reactions and interactions of the structure could be yielded [26]. In the literature, many articles are reporting about FE biomechanical analysis of orthodontic fixed braces [27–30]. So far, few studies have been made for

biomechanical modeling of orthodontic aligners [31–33], but many of them were much simplified and far from reality.

The aim of the current study was to report about designing a numerical realistic 3D finite element model that can be used to study the mechanical behavior of orthodontic aligners. Additionally, for validation of the model, we designed our model trying to simulate the same experimental setup used in some studies in the literature [13, 21, 34, 35] and then, the resultant forces generated — during facio-lingual translation of upper left central incisor tooth (tooth 21) — were compared with the reported values in these studies. Afterward, in future studies, modifications of the model will be done by adding the periodontal ligament (PDL) and the bone, in order to widely study the forces and the moments generated by the aligners with various teeth and in different directions of movement.

Materials and methods

A custom-made typodont model, already utilized for other experimental studies by our research team, was used in the current study. It was made up from acrylic teeth (Frasaco; Teltnag, Germany) and a resin (Technovit 4004; Kulzer, Wehrheim, Germany). The upper left central incisor (Tooth 21) was embedded malaligned 3 mm palatally in a pink wax, while the other teeth were aligned and fixed by the resin (Fig. 1). The typodont was scanned using a 3D lab-scanner (D2000; 3Shape, Copenhagen, Denmark). The generated digital model was exported as an STL file to a 3D image processing and editing software package (Mimics Innovation Suite, Mimics 24.0/3-matic 16.0; Materialise, Leuven, Belgium) (Fig. 1).

In 3-matic, the STL data were reconstructed to 3D surface models. The upper left central incisor (Tooth 21) was chosen as the treated tooth in the current study and was separated to be individually moveable. The first approach to design the aligner was to scan a thermoformed aligner; however, even with using special opaque sprays, the generated 3D scan was inaccurate, due to the transparency of the aligner. Additionally, many problems were met to establish a correct contact between the aligner and the teeth. So, the modeling tools of the 3-matic software were chosen to model the aligner with homogenous predefined thicknesses.

For aligner modeling, the surface element of the tooth crowns was selected and duplicated, with a clearance offset of 0.02 mm between the aligner and the teeth, and then by applying the solid uniform offset tool in 3-matic, full arch aligners were modeled. Four different thicknesses of the aligner were designed, namely 0.4, 0.5, 0.6, and 0.7 mm. Although thermoplastic sheets are supplied commonly in thickness of 0.75 mm, different thicknesses were modeled, referring to the material thinning resulted from

Fig. 1 Generation of a digital 3D model from a typodont model using a 3D-lab scanner
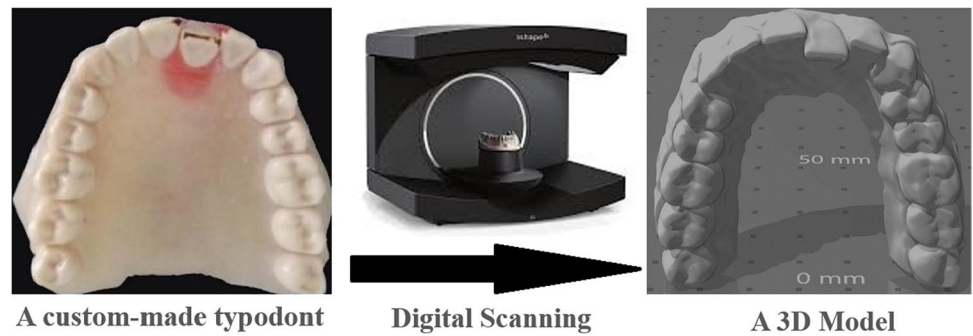
the deep-drawing process of the aligner sheet on the cast [35, 36]. Moreover, we considered the spacing foil (nearly 0.02 mm) at the internal surface of the aligner opposing to the tooth surface, defined by Elkholy et al. [23] as the primary offset, which is removed after thermoforming, and acting as an acceptable spacer for saliva and to facilitate removing of the aligner, along with delivering acceptable forces [37]. The sharp edges at the trimming line of the aligner were smoothened using the finishing/smoothing tool of 3-matic to get a scalloped design of the aligner margins following the gingival line of the teeth. Different trimming designs [38] are used in the market: scalloped, straight, and straight extended, but the scalloped design was chosen in the current study. In future studies, the effect of the trimming line design on the force transmission is planned to be investigated using the current FE model.

The 3-matic tool of adaptive element meshing was applied for re-meshing of the external aligner surface. By this tool, smaller elements were given at areas of complex geometry and larger elements at areas of less geometric complexity. The root with PDL and bone structures was not designed in the current study, to mimic the experimental conditions reported in earlier studies [23, 34] (Fig. 2).

The whole model was imported as 3-noded triangular surface elements model into an FE analysis pre-processing and post-processing software package (Marc/Mentat 2015; MSC Software, Los Angeles, Calif). In Marc/Mentat software, the triangular surface elements of the model were remeshed and converted to solid elements. A series of sensitivity analyses were performed to select the best parameters for the numerical simulation. For meshing of the aligner, different element classes and types were tried; 4-noded tetrahedral elements (Tetra 4), 10-noded tetrahedral elements (Tetra 10), 8-noded hexahedron (Hex 8), and 20-noded hexahedron (Hex 20), and the resulting values are reported in the current article. However, and based on the outputs, we selected (Tetra 4) for meshing of the cast and the teeth and (Tetra 10) for meshing of the aligner, and with these conditions, the number of elements and nodes of every part of the model are reported in Table 1.

In any FE simulation, the material model must be correctly specified to each component of the model. In agreement with many studies of hard oral tissues [27, 28, 31, 33], and for simplification of the model, the linear elastic constitutive mode was used. The Poisson's ratio was set at 0.3 for all structures [27, 30, 31, 33]. Young's modulus of teeth was chosen to be similar to enamel, without taking into

Fig. 2 Digital model of aligner and cast with separated moveable upper left central incisor (Tooth 21) for finite element studying of the orthodontic aligners
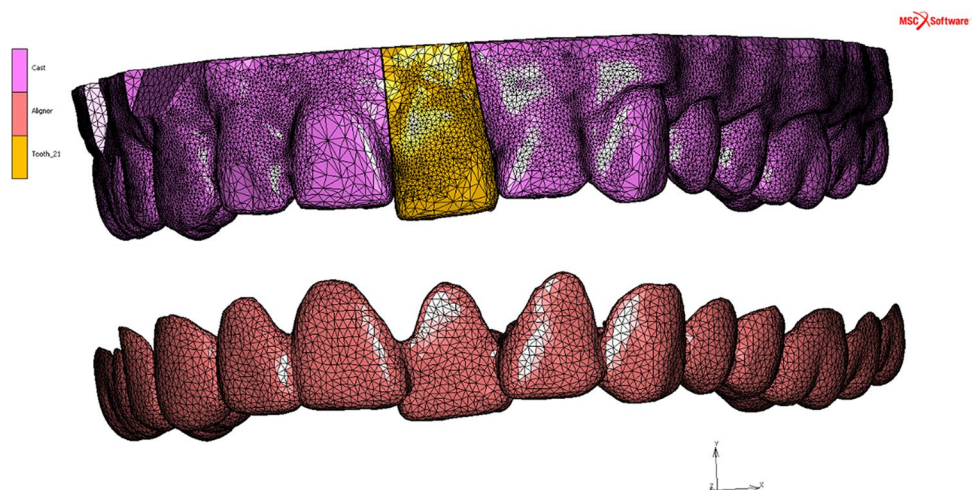
Table 1 Number and type of elements and nodes of all objects of the finite element model

Object	Element class/type	No. of elements	No. of nodes
Aligner 0.4 mm	Tetra 10, type 130	123226	245414
Aligner 0.5 mm	Tetra 10, type 130	186298	329915
Aligner 0.6 mm	Tetra 10, type 130	194323	338287
Aligner 0.7 mm	Tetra 10, type 130	380308	622539
Tooth 21	Tetra 4, type 157	13541	3450
Cast	Tetra 4, type 157	252808	62739

consideration the division into dentin, enamel, and pulp [31, 33]. Despite the large variations of the reported Young's modulus of enamel in literature from 18 GPa [27, 31] to 112 GPa [39], the value of 80 GPa was opted as reported in some recent articles [40, 41]. Nevertheless, in the current study, and by a sensitivity analysis, no significant difference was found when Young's modulus of 18 GPa for the teeth material was input. The reported Young's modulus of aligner materials in literature is in the range of 0.5 [33] to 2.2 GPa [42]. Young's modulus of aligner was elected to be 1.5 GPa, similar to a polyethylene terephthalate glycol-modified (PETG) thermoplastic sheets, commonly used for aligner fabrication and reported in some studies [42, 43]. Additionally, one of the aims of this study was to investigate the effect of the aligner's rigidity on the generation of forces; hence, the forces generated by 0.6-mm-thick aligners were calculated after varying Young's moduli: 0.5, 1.0, 1.5, and 2.0 GPa. Material parameters are shown in Table 2.

All components were defined as deformable (meshed) contact bodies. A contact table was created to define the contact interaction between different contact bodies. Contactless interaction was defined between the cast and the moveable teeth, while a touching sliding contact interaction was defined between the aligner and the tooth/cast surfaces, with a frictionless mode and with interference closure of -0.04. At the advanced contact control options of Marc/Mentat software, a node to segment method was used, and an optimized contact constraint equations mode was activated with a double-sided deformable-deformable method.

As the upper jaw model is arch-shaped, using the same coordinate system of the jaw for movement of the moveable teeth will not be correct. In other words, moving in Z-direction means a facio-lingual movement in anterior incisors but means mesio-distal movement in posterior molars.

Table 2 Material parameters assigned to aligner, cast, and teeth in the finite element model

Structure	Young's modulus (GPa)	Poisson's ratio
Plastic aligner	1.5	0.3
Cast and teeth	80	0.3

Additionally, the targeted Tooth 21 is following the curve of the arch. Therefore, for an accurate movement, a distinct local coordinate system should be defined for the tested separated Tooth 21 in a way that the X-axis pointed to the transverse mesio-distal direction, the Y-axis to the vertical intrusion-extrusion direction, and the Z-axis to the transverse facio-lingual direction, with the positive direction toward the facial, mesial, and intrusion of the tooth individually.

Boundary conditions were applied on the cast, the aligner, and the moveable tooth, through the structural fixed displacement function of Marc software. The cast was fixed in the 3 directions of translations at its lower surface nodes (a total of 3403 nodes). Moreover, the aligner was required to be preferably fixed during the simulation, which is somehow different from the clinical situation; however, some sort of numerical stability was necessary to be applied. For aligner fixation, a non-rigid indirect fixation was used at first, but many problems were faced in the model, so a rigid fixation was applied at nodes of the most distal ends of the aligner far from the loaded tooth, and the stresses at this fixed part were checked and found to be negligible. The movement boundary condition of Tooth 21 was applied to the surface nodes at the lower apical side (a total of 190 nodes). The Tooth 21 was loaded with a linearly increasing displacement in both facial ($+Z$) and lingual ($-Z$) directions to a maximum displacement of 0.2 mm, while it was fixed in the X- and Y-directions.

Calculations were performed on a computing cluster (Dell; Round Rock, Texas, USA). The calculation time and the data were somehow large. Therefore, as a trial to develop a more simplified model and for reducing the resultant data and decreasing the analysis time (reached 28 h), the size of the model was reduced, either by using an anterior segment or using half segment of the model, in which the span length of the aligner (distance between the two distal ends) would be shorter. However, there was a significant difference in the resultant forces between the full and the reduced model; hence, we ignored the reduced model, and our results in the current article are based on the full model (Fig. 2).

Results

The resultant forces from different aligner thicknesses on 0.2 mm facio-lingual translation of Tooth 21 were within the range of 1.3–18.3 N. A direction-dependency of force generation was displayed, in which lingual translation induced higher forces than facial translation (Fig. 3). Furthermore, the thickness of the aligner had a significant effect on force generation, where increasing the thickness generated higher forces, but the relation was not perfectly linear (Figs. 3 and 4). The course of the resultant force generation during the facial movement of tooth 21 by different aligner thicknesses

Fig. 3 Maximum resultant forces on 0.2-mm facio-lingual translation of upper left central incisor (Tooth 21) by aligner with different thicknesses
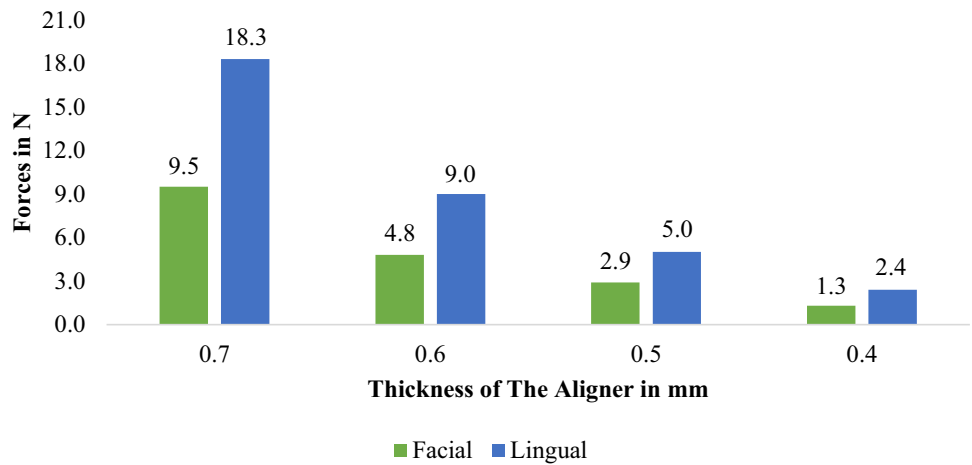
up to 0.2 mm is shown in Fig. 4, where an initial plateau of zero forces up to 0.02 mm can be noticed, corresponding to the initial gap between the teeth and the aligner, followed by a gradual increase of the forces reliant on both amount of displacement of the tooth and thickness of the aligner.

During the finite element model designing stage, selection of element classes and types was investigated in a sensitivity analysis. Using 20-noded hexahedron (Hex 20) or 8-noded hexahedral elements (Hex 8) for the aligner resulted in highest forces as well as high calculation times, while 10-noded tetrahedrons (Tetra 10) showed the lowest forces (Fig. 5) with moderate calculation time. Additionally, the rigidity of aligner material had a remarkable influence on the generated forces, where increasing the rigidity of the aligner generated higher forces, in the range of 500–2000 MPa of Young's modulus (Fig. 6).

The vector plot of Tooth 21 and aligner showed an extrusion tendency of the aligner during the displacement of Tooth 21 (Fig. 7). Moreover, a map of contact normal stresses showed an uneven distribution of contact normal stresses all over the surface, but a concentration of stresses at specific almost repeatable points at the mesial
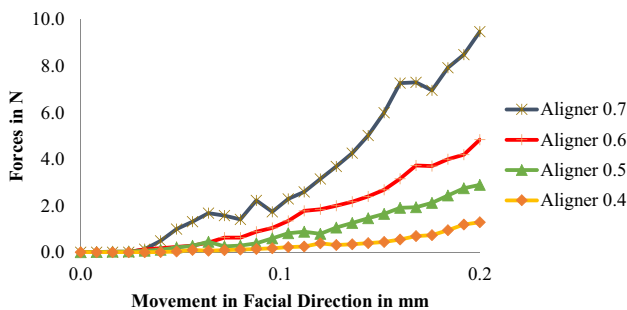
and the distal ridge of the facial surface, where the maximum contact normal stresses were 4.6, 32.9, 11.9, and 15.9 MPa with aligner 0.4, 0.5, 0.6, and 0.7 mm, respectively (Fig. 8).

Discussion

Biomechanical behavior of clear aligners is more complex compared to traditional fixed braces/wire orthodontic systems; many parameters are involved in determining the outcome of aligner treatment, and the force transferring interface is represented by the overall surface of the tooth crown, without a specific known point of force application [9]. Experimental and clinical methods have usually limitations in understanding these complex force systems. However, the combined efforts of having accurate mathematical modeling [44] and validated FE simulations [10] along with standardized experimental and clinical studies may reveal a lot about the biomechanics of orthodontic aligners [24].
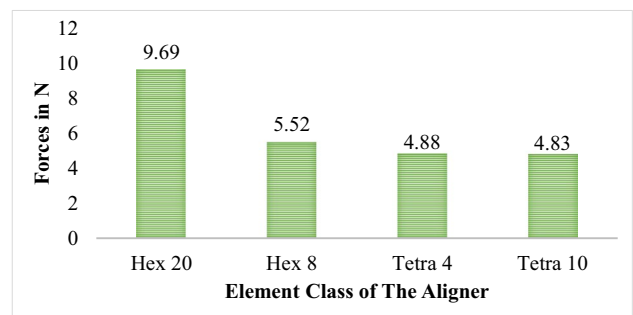

Fig. 4 Resultant forces during the course of 0.2-mm facial translation of upper left central incisor tooth (Tooth 21) by different thicknesses of aligner: 0.4, 0.5, 0.6, and 0.7 mm

Fig. 5 Maximum resultant force on 0.2-mm facial translation of upper left central incisor (Tooth 21) with aligner of 0.6 mm thickness on using different element classes for finite element meshing; 10-noded tetrahedral elements (Tetra 10), 4-noded tetrahedral elements (Tetra 4), 8-noded hexahedron (Hex 8), and 20-noded hexahedron (Hex 20)
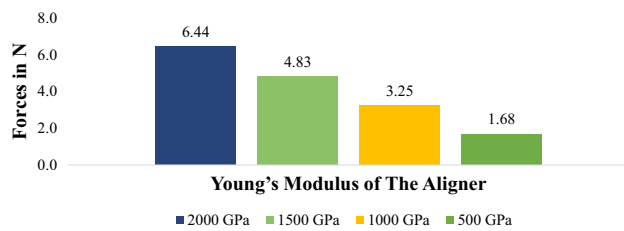
Fig. 6 Maximum resultant force on 0.2-mm facial translation of upper left central incisor (Tooth 21) with aligner of 0.6 mm thickness on using different aligner materials with different Young's modulus values

Therefore, we are aiming in the current article to report about designing a validated FE model, in order to better understand the mechanics of orthodontic aligners.

In FE simulations, the form of meshing has a significant impact on the outcomes [45], and choosing the appropriate element class play a crucial role in the simulation and affect the quality and accuracy of the numerical analysis [46]. Therefore, 4-noded tetrahedral elements (Tetra 4) were used for meshing of the cast and the movable tooth,

suitable for their rigidity, while 10-noded tetrahedrons (Tetra 10) were selected for the aligner, coping with its flexibility. Tetra 10 were opted for the structures that might show large displacements/large strains or nonlinear behavior, like aligner. Also, Dumont et al. [45] reported that the mathematical model behind Tetra 10 element keeps a linear relationship between stress and strain over the element volume, while in Tetra 4 element, the stress and strain stay almost constant. The mathematics behind tetrahedron element type is as robust as for a hexahedron. However, after a sensitivity analysis, the result of the hexahedral model has been excluded due to the extreme calculation times and higher generated forces, while the results with Tetra 10 were more accepted, as shown in the results.

Determination of the contact parameters between the aligner and the teeth is tricky, due to the high irregular and customized shape of the aligner which made the exact formulation of load distribution more difficult [10, 31]. Significantly higher resultant forces were found in load cases considering friction. Hence, friction was neglected between the aligner and the teeth, as chosen by Cai et al.

Fig. 7 Vector plot of facial (left) and lingual (right) 0.2-mm translation of upper left central incisor (Tooth 21) showing direction of aligner displacement
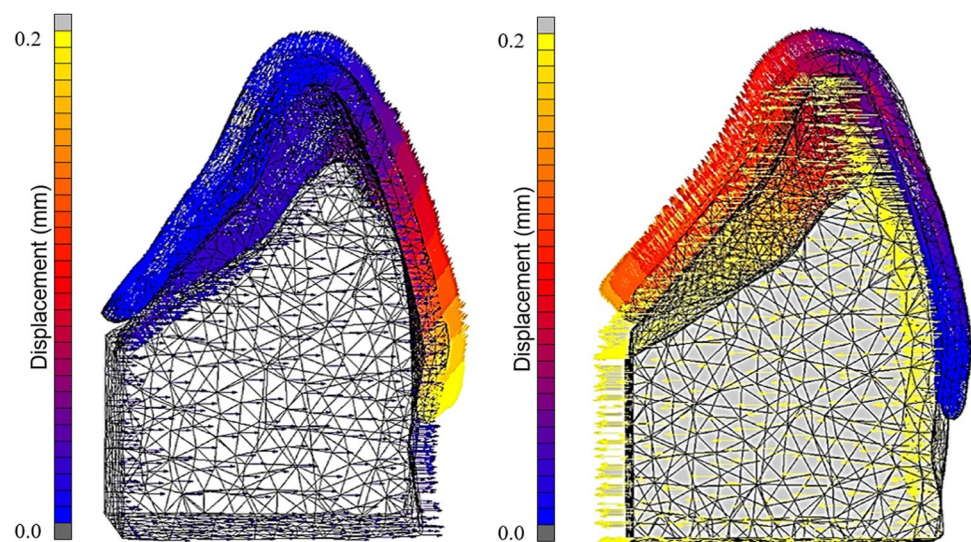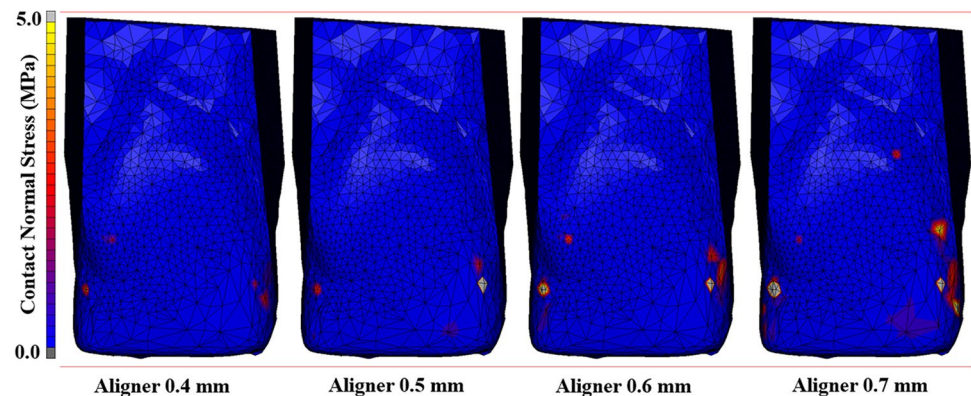

Fig. 8 Visual representation of the areas of contact normal stress (MPa) generated on 0.2-mm facial translation of upper left central incisor (Tooth 21) with different aligner thicknesses

[32] and Barone et al. [31], referring to the existence of dissimilarity between the aligner material and the tooth tissue, and taking into consideration the in-between presence of saliva acting as a lubricant. On the opposite, Gomez et al. [33] defined a friction coefficient of 0.2 in their simple model.

In the current FE model, the movement was applied on the tooth, while the clinical condition is totally the opposite, where the aligner is thermoformed onto a prototyped model with the target tooth already moved. Nevertheless, the resulting loading condition is the same, following Newton's third law, with the advantage that the aligner must be modeled only one time, and afterwards, different types of orthodontic tooth movements can be simulated and analyzed in the FE software [31].

In order to reduce the big resultant data, and for decreasing the analysis time, the size of the model was reduced. However, opposite to a report by Barone et al. [31], the shorter model showed a significant difference in the resulting forces; hence, we depended on the full model in the current study. That is actually in harmony with the concept reported by Hahn et al. [37] and Elshazly et al. [3] that the aligner is retained in the molar region and the whole aligner becomes deformed by the moveable tooth like a bow; the moveable tooth makes a deflection, in which the maximum deflection force increases with decreasing the length of the aligner and vice versa [47, 48].

From a biomechanical point of view, clinically during tooth movement, the tooth could move in six degrees of freedom. The type of tooth movement is determined by the relationship between a direction of force vector and the location of its center of resistance. When the force vector passes through the center of resistance, it causes bodily tooth movement [49]. The center of resistance of a single rooted tooth was described at roughly 42% of the height of the alveolar bone, from the alveolar bone crest to the tooth root apex, irrespective of root length and direction of loading [50]. Vollmer et al. [51] reported a significant difference between the movement generated in the idealized models and the realistic model, due to the continuous change of the center of resistance, and hence, it is almost very difficult to simulate the clinical translation movement with idealized models. Also, the orthodontic movement is based on geometrical considerations of both, the crown and the root, as well as their surroundings. Hence, neglecting root geometry, PDL, and bone, as well as applying the boundary conditions as a pure translation movement in 1D, is one of the major limitations of current study, and such simplification would bring somehow to inaccurate outcomes [31]. However, for validation, similar experimental conditions should be simulated, as the PDL is excluded in the experimental studies.

The obtained force values on 0.2-mm facio-lingual translation of Tooth 21 are in the range of 1.3–18.3 N, consistent with experimental reports by Hahn et al. (3.9–5.4 N) [22, 37] and Elkholy et al. (2.3–10.2 N) [13, 23], in which they

used customized biomechanical measuring systems. Also, Li et al. [18] used a micro-stress sensor system and reported force levels at 7.7 N. Moreover, Xiang et al. [17] reported instant force values around 8.0 N by conventional PETG aligners measured by a thin-film pressure sensor. The slight dissimilarity could be referred to the variation in the experimental set-up. On the contrary, Simon et al. [21] reported lower force levels at 0.2–1.5 N. This difference could be due to the flexibility in their experimental set up and use of an ideal center of resistance for measured teeth. In harmony with previous reports by Hahn et al. [52] and Elkholy et al. [35], it was clear that the higher the Young's modulus of aligner material, the higher was the generated forces (Fig. 6).

Indeed, a lot of consideration should be put in mind while comparing the experimental condition with the idealized finite simulations. In the experiment, there are a lot of factors which could affect the results. For example, in the FE model, a homogenous thickness of aligner with a pre-defined values (0.4, 0.5, 0.6, and 0.7 mm) was modeled; however, in the experimental situation, there is a great thickness variations of the aligner all over the surface of the teeth referred to the thermoforming over the uneven surfaces of the cast. This local thinning of aligner material (which would not be simulated in the current model) would affect the experimental results significantly. Additionally, for simplification, a linear model of material was applied, but in reality, the material reaction with the experimental model may be somehow different. Moreover, although the experimental set-ups are rigid, there is still some sort of flexibility of the devices which is not considered in the mathematical FE model. All of this mentioned points, and more, could make differences on the order of some Newton but that is still accepted for validation.

Nonetheless, the resulting forces are still higher than the ideal orthodontic forces for bodily movement (0.75–1.25 N) [47, 48]. The absence of PDL is most probably the reason behind this. In addition, some studies [13, 14, 22, 52, 53] reported that the initial forces by aligners may exceed six times the recommended values for orthodontic movement, followed by a dramatic decrease of the forces. Also, alterations in the properties of the aligner material by the effect of the intraoral conditions may indorse force decay to a possible limit similar to, or even lower than, bracket system despite the high initial forces [54].

In agreement with some experimental studies [37, 53, 55, 56], increasing the thickness of the aligner leads to increasing of the generated forces, which is also in harmony with the clinical findings [35] that the risk of root resorption is lower with aligners of reduced thickness. However, indeed, the direct proportionality is apparently not perfect. That could be understandable in a way that the deformation of the aligner is a combination of bending (influence of the thickness with a power of 3) and stretching (direct proportionality). Checking this behavior by comparing with Figs. 3

and 4 shows that force increases stronger than linear. Also, the direction-dependent pattern of the force–displacement curves is likely due to the different facial and lingual morphologies of an upper central incisor [13, 23, 37].

In Fig. 4, the forces do not increase monotonically with displacement and there are unexpected decrease in forces at some intervals of the force/displacement graph. That could be referred to the nature of the idealized surface of the FE model, where there are many triangles and nodes, at which slipping may occur during the simulation, and especially with neglecting the friction, this slipping is reflected as decrease in the forces at some intervals.

From the vector plot of the displacement (Fig. 7), and in agreement with others [13, 22, 23, 52], the facio-lingual displacement of Tooth 21 is clearly accompanied with an intrusive force applied to the tooth referred to the morphology of the tooth that affects the force distribution over the surface and leads to analysis of the force vectors into horizontal and vertical components.

Despite that the orthodontic aligner move teeth by pushing rather than pulling, which should lead to an intimate contact between the aligner and the tooth surface, however, the uneven topography of the tooth surface affects significantly the stress distribution. In harmony with a study by Cervinara et al. [19], there is an uneven distribution of contact normal stress all over the surface of the tooth 21; where there are areas of relief and others with intimate contact, therefore, the force level differs from point to point all over the surface. However, there are an almost repeatable pattern of stress concentration areas/points which could be considered as the point of application of the force (Fig. 8). Excluding the aligner of 0.5 mm thickness, we saw that the stress at these points increased by increasing of the aligner thickness. The very high abnormal stress concentration in case of 0.5-mm aligner could be ignored and referred to a node to node early interference. Nevertheless, the total resultant force/deflection values with 0.5-mm aligner are in raw with the values of other aligners (Fig. 4). Also, the stress concentration mostly at the inciso-mesial and inciso-distal parts could create some sort of lingual-torque moment, owing to eccentric force application at the incisal crown level, in one line with a previous study [13]. Cervinara et al. [19] reported mean stress values at the active areas up to 5.0 MPa and a total pressure value of 15 MPa with 0.7-mm-thick aligner. In Fig. 8, we used the same color scale for the different thicknesses which might lead to absence of some stress points, due to being below the stress limit of the presentation color scale; however, with a more meticulous checking of the stress pattern generated by each thickness individually, we could confirm the repeatability of the stress distribution pattern. Additionally, we should put in mind that the increase of the aligner thickness would affect its bending ability and mobility, hence a slight shift of the stress points between the different thicknesses would be expected.

The current study has some limitations mentioned through the whole article. However, modifications of the model, to approach the realization, will be done in further publications. A more detailed demonstration of the generated forces and moments is to be reported after adding the PDL and bone in future studies. In addition, different trimming line levels of the aligner and different movements of several teeth will be reported.

Conclusions

1. FEM is a promising alternative approach that might lead to a better understanding of the mechanical behavior of orthodontic aligners. The current model has limitations; however, further studies and modifications of the model, to approach the realization, are going on.
2. The deformation of the aligner is a combination of bending (influence of the thickness with a power of 3) and stretching (direct proportionality).
3. The biomechanical concept of the aligner/tooth interaction could be represented as an arrow within a bow, in which increasing the deformation range and/or the span length will generate higher force.
4. Aligner material parameters must be carefully considered in order to deliver the optimal forces for orthodontic tooth movement.
5. In FE simulation, the mesh element class and type should be carefully opted as they significantly affect the results of the model. Based on our simulations, 4-noded tetrahedral elements (Tetra 4) are recommended for meshing of the teeth, and 10-noded tetrahedral elements (Tetra 10) for meshing of the aligner.

Declarations

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

Informed consent Not applicable.

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