

Custom-Fitted EVA Mouthguards: what is the ideal thickness? a dynamic finite element impact study

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Abstract – Background/Aim: The aim of this study was to evaluate the tooth stresses and strains, shock absorption, and displacement during impact of custom-fitted mouthguards with different thicknesses. **Methods:** Six bar-shaped specimens of the EVA were made and subjected to tensile test for elastic modulus assessment. Two-dimensional plane-strain models of a human maxillary central incisor, periodontal ligament, bone support, soft tissue, and mouthguard (MTG) were created. The mouthguards were modeled in five different thicknesses (2, 3, 4, 5, and 6 mm). One model was created without mouthguard. A nonlinear dynamic impact analysis was performed in which a rigid object hit the model at 1 m s^{-1} . Strain and stress (von Mises and Critical modified von Mises) distributions were evaluated, and the displacement of the mouthguard with respect to the tooth was calculated. **Results:** The mean [SD] for the EVA elastic modulus was $18.075 [0.457] \text{ MPa}$. The model without mouthguard showed the highest stress values at the enamel and dentin structures in the tooth crown during the impact. For the MTG models, the location of the stress concentrations changed to the root, regardless of the MTG thickness, but maximum stresses in the enamel and dentin were lower compared with the model without MTG. Increasing the mouthguard thickness did not notably decrease the stress-strain values. **Conclusion:** It was concluded that the use of a mouthguard promoted lower stresses and strains in teeth during an impact with a rigid object. There was no substantial difference in peak stresses and strains and in shock absorption among the different mouthguard thicknesses.

The majority of oral-facial injuries are related with sports activities (1–3). However, most of these injuries can be prevented using protective devices, such as headgears, mouthguards (mouth formed, stock, and custom-fitted), helmets, and protective facemasks (4–6). Mouthguards are specially designed for dental trauma prevention during contact sports (5, 7–9). Their primary function is to prevent direct violent contact with tooth structures and between the upper and lower dentition. Mouthguards also absorb energy generated by the impact and reduce the forces transmitted to the teeth. Positive effects of mouthguards made from ethylene vinyl acetate (EVA) copolymer and their shock absorption ability have been shown in various studies (10, 11). Among the different mouthguard types, custom-fitted mouthguards provided superior performance in terms of comfort, fit, stability, respiratory capacity, phonetics, and protection for dental structures (12–14).

Mechanical performance of mouthguards in terms of shock absorption is affected by several factors, such as material type, geometry, manufacturing process, and thickness. These factors also influence the fit, comfort, and wearability (15). Although these factors influence the mouthguard performance, the thickness is perhaps the most important parameter for shock absorption (9, 16). The thickness of custom-fitted mouthguards can be influenced by heating and fixation during the manufacturing process and by sheet geometry (17, 18). Several studies reported that the shock absorption ability is improved by increasing the thickness (16, 19, 20). On the other hand, thicker mouthguards are related with poor athletic performance, respiratory efficiency, and comfort issues. Some authors reported that 4 mm seems to represent the ideal thickness to provide sufficient shock absorption and comfort (12, 15, 16).

Experimental impact tests have been used to evaluate mouthguard performance (21–23). However,

internal stress distributions cannot be obtained from typical impact tests. Therefore, shock absorption mechanisms of mouthguards and stress distributions over the tooth structures are still unclear. Finite element analysis is a powerful engineering tool that can calculate the stress and strain behavior of the materials in response to load application. The aim of this study was to use finite element analysis for the evaluation of internal stresses and strains, shock absorption, and displacement of custom-fitted EVA mouthguards for different thicknesses (2, 3, 4, 5, and 6 mm).

Materials and methods

Elastic modulus assessment of ethylene vinyl acetate (EVA)

Six bar-shaped specimens of the EVA (Bio-art, São Carlos, SP, Brazil) were made ($70 \times 10 \times 3$ mm). The specimens were attached to two pneumatic clamps (2712 Series Pneumatic Action Grips, Instron Corporation, Norwood, MA, USA). The initial length between the clamps was measured using a digital caliper before starting the test. The specimens were subjected to a nondestructive tensile load from 0 to 150 N at cross-head speed of 500 mm min^{-1} using a universal mechanical testing machine (Instron 5500 Series, Instron Corporation). The load/displacement data were recorded by dedicated software (BlueHill 2, Instron

Corporation). The strain (ϵ) was calculated as the ratio of the displacement and initial length between the clamps, and the stress (σ) was determined as the ratio of the load and cross-sectional area of each sample. The elastic modulus (E) was calculated from the middle portion of each stress-strain curve (avoiding the initial alignment slack of the clamps): $E = (\sum \Delta\sigma/\Delta\epsilon)/N$, where $\Delta\sigma$ is a stress increment and $\Delta\epsilon$ is a strain increment, and N is the number of data points. This mean elastic modulus of the six samples was applied in the finite element analysis.

Two-dimensional dynamic finite element impact modeling

Two-dimensional models of a human maxillary central incisor, periodontal ligament, bone support (cortical and trabecular bone), soft tissue, and mouthguard (MTG) were created based on a CT-tomography image of a patient with normal occlusion (Angle Class I) wearing a mouthguard (Fig. 1a). The image was exported to an image processing and analysis software (Image J, public domain, National Institute of Health, Bethesda, MD, USA) for tracing coordinates of the tissue outlines. The coordinates obtained (Fig. 1b) were imported in a finite element analysis program (Marc/Mentat, MSC software, Santa Ana, CA, USA), and cubic-spline curves were created through these coordinates to recreate the tissue outlines (Fig. 1c). A model

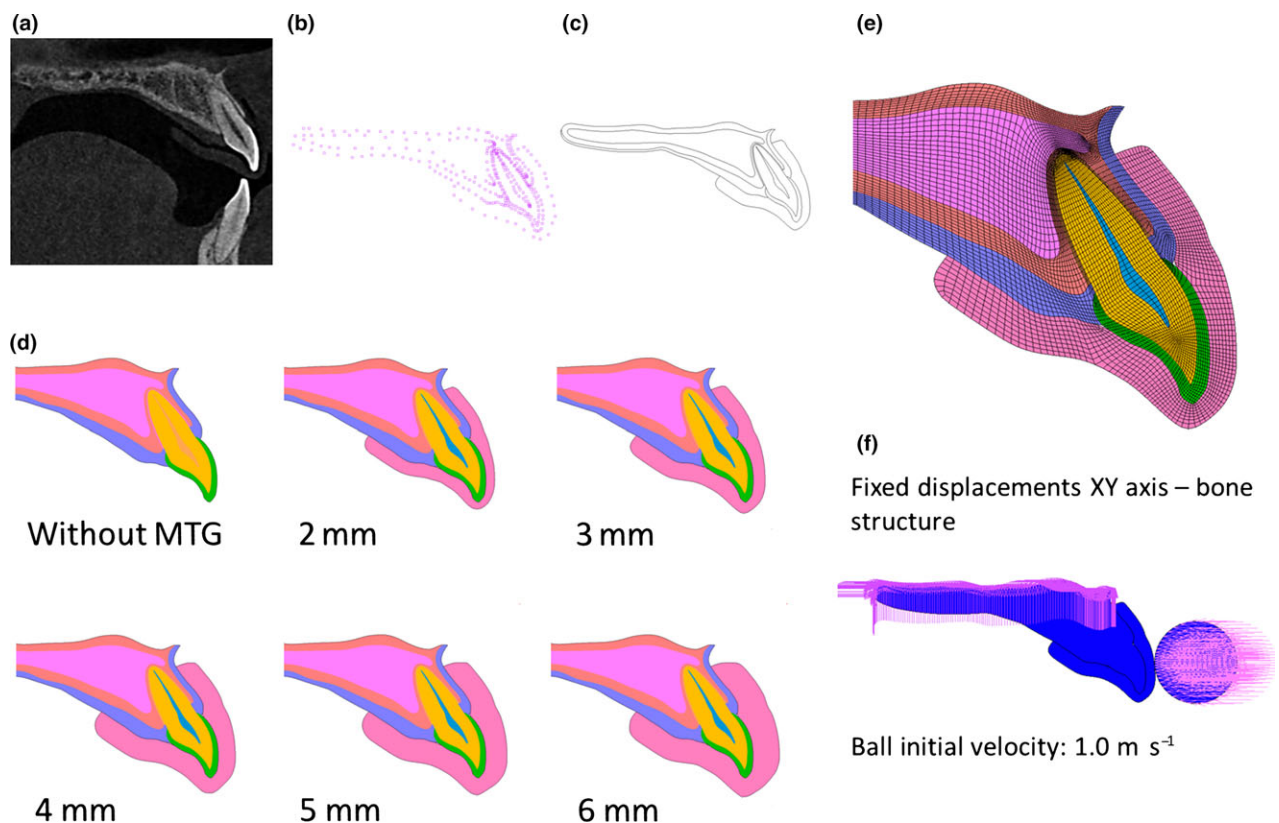


Fig. 1. Generation of two-dimensional finite element models. (a) CT-tomography image of maxillary central incisor with MTG; (b) coordinates points of the CT image imported from Image J; (c) cubic-spline curves generated from the coordinates; (d) two-dimensional models created without mouthguard and with 2-, 3-, 4-, 5-, and 6-mm-thick mouthguards; (e) finite element mesh distribution (with 6-mm-thick mouthguard); (f) boundary conditions.

without mouthguard (Without MTG) and five models with mouthguards of different thicknesses were created (2-mm MTG, 3-mm MTG, 4-mm MTG, 5-mm MTG, and 6-mm MTG) (Fig. 1d). The geometries of the mouthguards were created based on the CT image of a patient wearing a 3 mm custom-fitted MTG. By adjusting the original 3-mm MTG to 2, 4, 5, or 6 mm thickness, the other MTG models were created. The element mesh was manually created using four-node isoparametric arbitrary quadrilateral plane-strain elements with reduced integration (one integration point per element—element type number 115 in the Marc/Mentat software) (Fig. 1e).

Frictionless contact was prescribed between the mouthguard and the model interface, and separation between them was allowed during the impact. All other interfaces were considered bonded. A dynamic impact analysis was performed using the Single-Step Houbolt method. This algorithm is recommended for implicit dynamic contact analyses (24). A rigid impact object (steel) was simulated, and a 1.0 m s^{-1} initial velocity was applied to all the nodes of the impact object in the x -direction (Fig. 1f), but the impact object was unrestrained after this initial velocity was applied. No gravitational forces were modeled. The nodes on the base of the bone structure were rigidly fixed in the x - and y -directions (Fig. 1f). All materials were considered linear, isotropic, and homogeneous. The mechanical properties (elastic modulus, Poisson's ratio, and material density) are shown in Table 1.

Each model was solved in Marc, and the results were analyzed until the impact object lost contact with the mouthguard. During the analysis, a custom-made subroutine (Fortran-based) recorded the strain values in the Y direction for one node at the palatal side. Based on the peak strain values (maximum impact), the shock absorption capability was calculated for each mouthguard thickness, defined as the percentage of the peak value of the model without mouthguard. This program also recorded the 10% highest stresses in the enamel and dentin during the impact. The stress distributions were analyzed using von Mises equivalent stresses, which integrate all stress components into one stress equivalent value. Additionally, the Critical modified von Mises stresses were determined to show critical

areas for structural failure at the impact. The Critical modified von Mises stress takes the difference between compressive and tensile strengths into account and scales the equivalent values relative to their tensile strength (critical stress ratio). The compressive and tensile strengths of enamel were 384.0 and 10.3 MPa and for dentin 297.0 and 98.7 MPa, respectively (25).

Finally, the contact status between the mouthguard, tooth, and impact object was evaluated. The distances between nodes on the mouthguard and the tooth model (contact separation) were calculated during the impact analysis to characterize the mouthguard displacement

(mm): $d = \sqrt{\{(x_2 - x_1)^2 + (y_2 - y_1)^2\}}$, where d is the mouthguard displacement away from the tooth, x_1 and y_1 are the x - and y -coordinates of the node at the tooth surface, and x_2 and y_2 are the coordinates of a corresponding node on the mouthguard surface (Fig. 5a).

Results

Elastic modulus of EVA

The mean [standard deviation] for the EVA elastic modulus was 18.075 [0.457] MPa. This value was used in the finite element analysis.

Dynamic finite element impact analyses

Stress distributions in the model without MTG and in the different MTG models at the peak of the impact are shown in Fig. 2. The stress values are visualized according to a linear color scale: blue indicating the lowest stress values, yellow and light gray the highest stress values. The mean of the 10% highest stresses for enamel and dentin during the impact analysis is shown in Fig. 2g and h. The model without mouthguard had the highest stress values at the enamel and dentin structures in the tooth crown during the impact (Figs 2a, g, and h). For the MTG models, the location of the stress concentrations changed to the root, regardless of the MTG thickness, and maximum stresses in the enamel and dentin were lower than they were in the model without MTG (Fig. 2b–f). Increasing the mouthguard thickness did not notably decrease the stress values (Fig. 2g and h).

The history plot for the strain values at the palatal side of the tooth and the strain peak values are shown in the Fig. 3. The model without MTG showed a high strain value compared to the MTG models (Fig. 3a). Among the models with mouthguard, the 2-mm-thick mouthguard exhibited the highest strain values and lowest shock absorption (Fig. 3b). The history plot showed that the time to reach the peak strain was longer with the 3-mm and 4-mm mouthguards, but further increasing the thickness to 5 or 6 mm yielded similar times to peak as found for the 2-mm MTG model (Fig. 3a).

The distribution of the Critical modified von Mises stress showed that for the model without mouthguard the critical area for structural failure at impact was at the palatal side (Fig. 4a). The path plot of the mouthguard displacement for each MTG model is shown in

Table 1. Mechanical properties applied for the dental structures and materials

Structure	Elastic Modulus (MPa)	Poisson's ratio	Density (g cm^{-3})	References
Enamel	84 100	0.30	2.14	(27)
Dentin	18 600	0.30	2.97	(28)
Periodontal ligament	50	0.45	0.95	(29)
Trabecular bone	1400	0.31	0.70	(30)
Cortical bone	13 700	0.33	2.00	(30)
Soft tissue	1.8	0.30	0.95	(31)
Steel	200 000	0.30	7.8	(32)
EVA	18.075*	0.30	0.95	(33)

*Experimentally determined in this study.

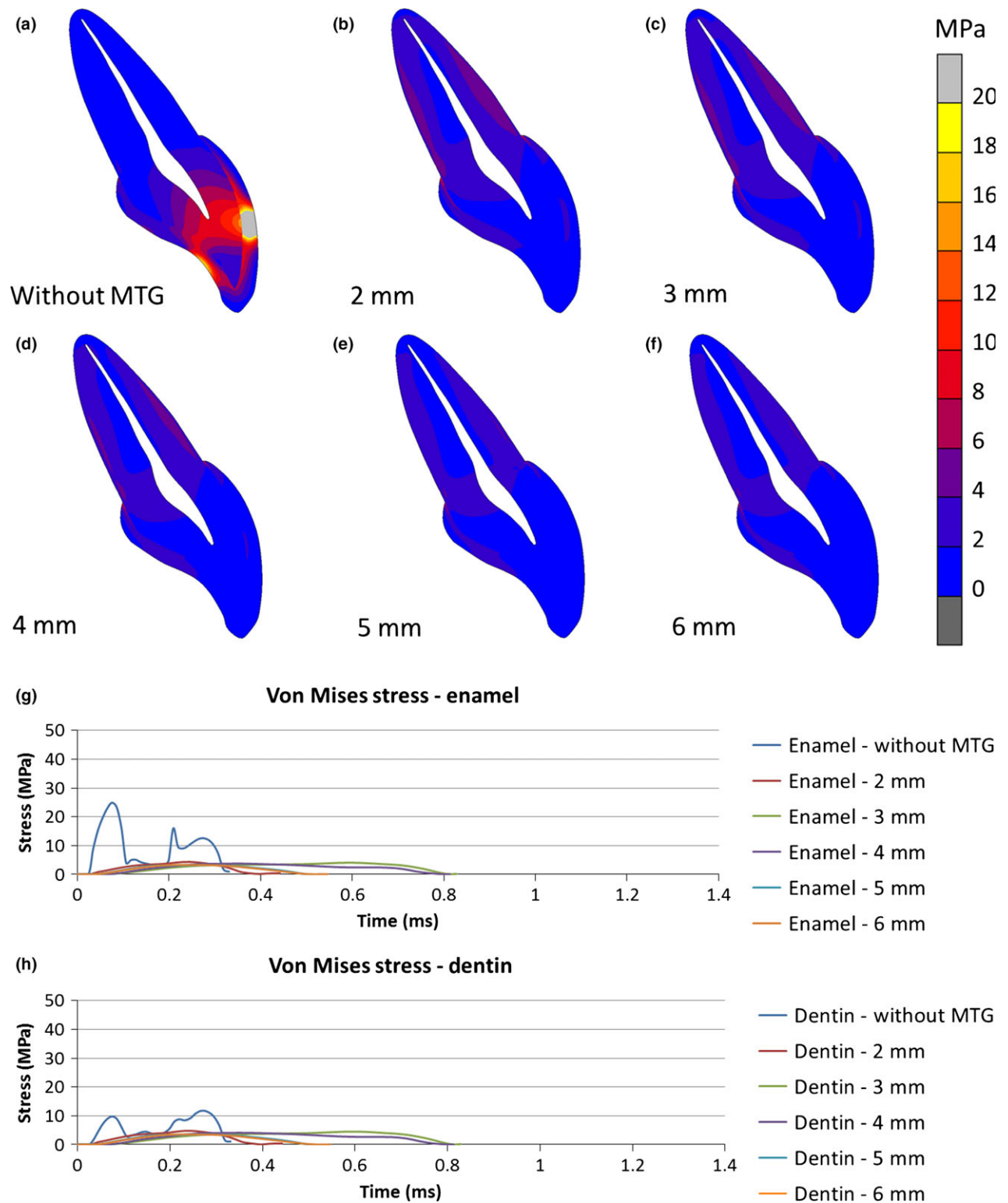


Fig. 2. Von Mises stress distributions at the peak of impact (a) without MTG; (b) 2-mm MTG; (c) 3-mm MTG; (d) 4-mm MTG; (e) 5-mm MTG; (f) 6-mm MTG; (g) mean of 10% highest stress values for enamel; (h) mean of 10% highest stress values for dentin during the impact.

Fig. 5. The different mouthguard thicknesses resulted in different patterns of mouthguard displacements. Increasing the mouthguard thickness decreased the

mouthguard displacement on the buccal side at the end of the impact. The 2-mm MTG and 3-mm MTG showed higher displacement at the buccal side. The

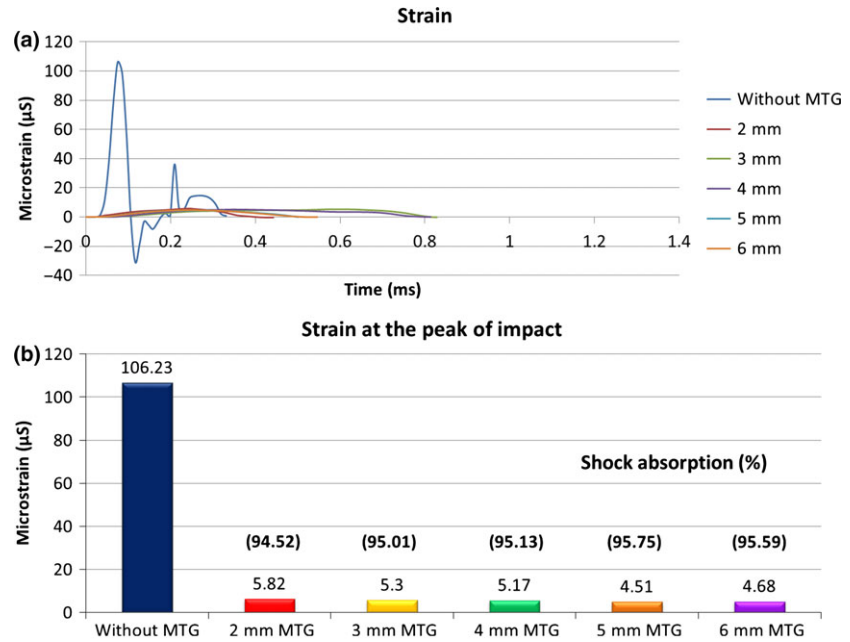


Fig. 3. Strain values at the palatal side of the tooth. (a) History plot during the impact; (b) microstrain values at the peak of impact and percentage shock absorption in parentheses.

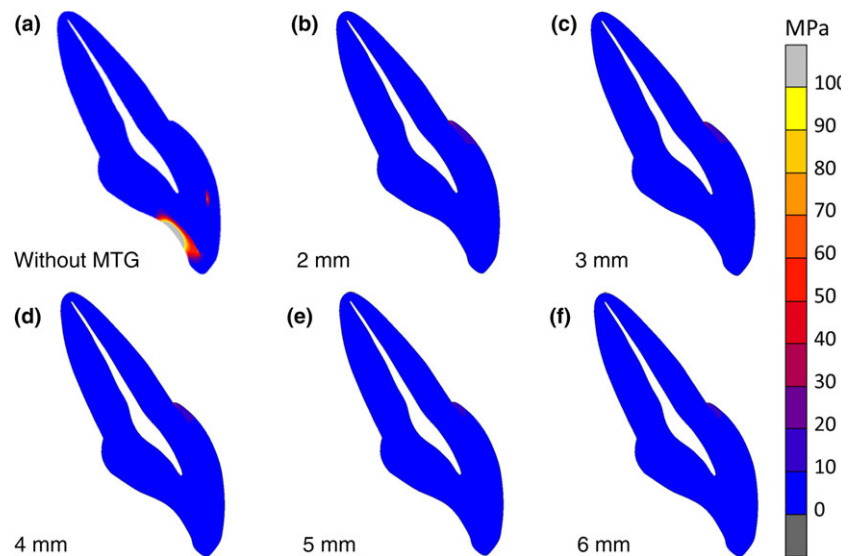


Fig. 4. Critical modified von Mises stress distributions at the peak of impact. (a) Without MTG; (b) 2-mm MTG; (c) 3-mm MTG; (d) 4-mm MTG; (e) 5-mm MTG; (f) 6-mm MTG.

6-mm MTG showed lower displacement at the buccal side.

Discussion

Mouthguard thickness is one of the most important contributing factors for the mechanical performance and shock absorption ability of mouthguards. The standard method for custom-fitted mouthguard production is to press a sheet of thermoplastic material against a plaster model by means of a vacuum-forming machine. Several studies showed the influence of the fabrication process (holding and heating process) on the final thickness of a mouthguard. Different techniques have been developed to ensure optimal final thickness during the manufacturing process (17, 18). Mouthguards with thicknesses ranging from 2 to 6 mm

have been evaluated in the literature. Most recent studies show that 3 or 4 mm thickness provides sufficient protection and comfort during the use (16, 19, 20). Impact testing has extensively demonstrated that the mouthguard thickness has an inverse relationship with the force transmitted (16). Nevertheless, experimental impact tests cannot show the stresses and strains that are generated internally in the tooth structure and in the bone support during an impact.

Finite element analysis may be the only approach that can predict stress and strain behavior of the materials and structures during impact load. This study used a nonlinear dynamic finite element impact analysis to evaluate the stress distributions and strains assuming a plane-strain condition in the structures. Although the model is 2D, the plane-strain condition represents a three-dimensional condition that may occur in the cross

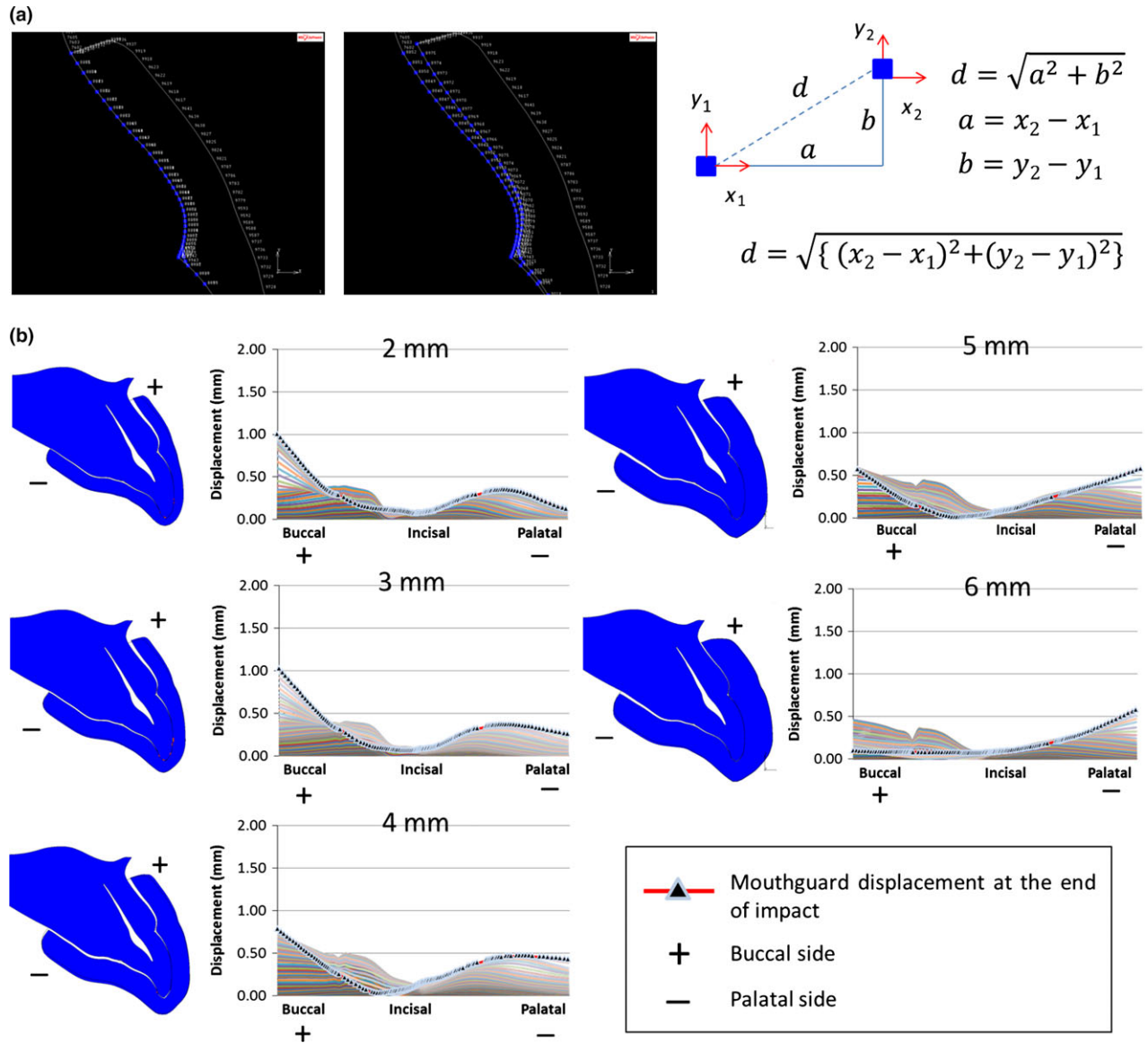


Fig. 5. Path plot of the mouthguard displacement (mm) during the impact application.

section of a structure with considerable thickness out of the plane, which is true for the modeled cross section where the strain perpendicular to the cross-sectional plane is zero (25). In a previous validation study, it was shown that despite the simplified tissue properties, the finite element impact simulation showed a similar behavior as observed in an *ex vivo* impact experiment (34). Dynamic analyses are different from more common static analyses because at high loading rates the inertia forces cannot be neglected. In the current dynamic analysis, the impact object's velocity and inertia were the initial conditions that determined the time-dependent forces to which the tooth and mouthguard models were subjected. Besides the dynamics, the interface between the impact object, mouthguard, and tooth is also important for a realistic impact response. In most of the previously published finite element analyses, the tooth and mouthguard elements shared the

same nodes at their interfaces, which means that they were perfectly bonded. However, in reality mouthguards are not bonded to the tooth surface nor the soft tissues. The current study applied nonlinear contact analysis between the impact object, mouthguard, and tooth model to predict their interactions and displacements more accurately during the impact. Although the periodontal ligament presents viscoelastic behavior, our study modeled this structure using an elastic assumption. This elastic assumption was chosen because at high speed and impact situations there is a little time for the periodontal ligament express this time-dependent property. In this sense, the viscoelastic properties are very important for studies that the forces are applied sufficiently slowly that the inertia is not so important.

The results of the finite element analysis showed that the mouthguards reduced maximum stress and strain

values in both enamel and dentin for all thicknesses. The compliant EVA material of the mouthguards absorbed most of the impact deformation, which increased the time to absorb and redistribute the impact forces and thus decreased the stress and strain on the tooth structure. The presence of a mouthguard therefore allowed the stresses caused by the impact to be distributed through the dentin structures into the bone, which resulted in lower strain values at the palatal side of the crown. This behavior can be observed in Fig. 2. Preliminary studies determined that the relationship between the deformation of teeth with or without mouthguard is a good indicator for the efficiency of these devices in terms of design and ability to prevent traumas (21). In this study, a higher strain value was obtained with the 2-mm-thick mouthguard and consequently its shock absorption ability was lower than with the thicker mouthguards. With each increase in mouthguard thickness, the peak strain value decreased slightly up to the 5 mm thickness, after which a small increase in peak strain was noted for the 6-mm MTG. Apparently, beyond 5 mm the structural stiffness and inertia increase of the mouthguard caused by the added thickness became more influential than the absorption offered by the thicker EVA layer. This mechanism can be seen in the reduction in bounce-back time of the impact object (Fig. 3a).

Crown fracture without pulp exposure is the most frequent dental trauma injury, with an occurrence of 36% compared to 24% concussion and 22% subluxation (26). Therefore, information related to location and propagation of crown fracture is vital for treatment, prognosis, and prevention of dental traumas. The Critical modified von Mises method was used to assess the critical areas for structural failure. An impact load horizontal to the dentition and without mouthguard created a potentially critical condition for fracture at the palatal side of the tooth crown (Fig. 4a). This stress condition implies bending of the crown at impact, causing compression in the enamel on the buccal side and (critical) tension in the enamel at the palatal side. Presence of mouthguard prevented this critical condition regardless of the mouthguard thickness.

Custom-fitted mouthguards are individually made and thus offer advantages in terms of comfort, fit, stability, phonetics, and respiratory capacity (12). Mouthguard displacement is an important parameter for the impact absorption because a mouthguard should stay in position to function correctly. The dynamic finite element impact analysis in this study showed that there is a relationship between the mouthguard thickness and the pattern of mouthguard displacement. Thin mouthguards (2 and 3 mm) have higher displacements at the buccal side. These suggest that a thicker mouthguard can prevent mouthguard displacement during an impact. However, other factors, such as soft tissues, proximal areas, and tooth surfaces, are involved in the mouthguard retention and fit. Further research using three-dimensional (3D) modeling may be necessary to further study these relationships.

The balance between mouthguard thickness and its comfort is critical for athletic performance and wearing

compliance. Thick mouthguards (6 mm) are likely to cause discomfort, respiratory issues, and have poor acceptance (15). Lips and cheeks are the natural barriers that help to protect the teeth from a direct impact. However, a 6-mm mouthguard can jeopardize this natural protection and not allow the lips to cover the teeth (15). Furthermore, thicker mouthguards can increase the tension between the lips and cheeks, which increases the risk of soft tissues injuries.

Conclusion

From this study, it can be concluded that the use of a mouthguard promoted lower stresses and strains in teeth during an impact with a rigid object and that there was no substantial difference in peak stresses and strains and in shock absorption among mouthguards that were 4 to 6 mm thick. In addition, increasing mouthguard thickness decreased the mouthguard displacements. Considering the results of the finite element impact analysis and the discussed concerns about comfort, mouthguard thicknesses of 3–4 mm can be recommended for custom-fitted mouthguards.

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