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Evaluation of Impact Absorption and Stress Distribution on Anterior Teeth and Maxilla Using Conventional and Modified Mouthguard on Application of Horizontal Forces on Maxillary Anterior Teeth In 20-Year-Old: A 3D Finite Element Analysis

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Abstract

Background: The use of protective devices while sports activity is crucial as it has been reported that trauma as a result of sports activities represent up to 1/3rd of all orofacial injuries. 4 mm appears to be the optimal thickness for adequate shock absorption to ensure optimal shock absorption and comfort. One proposed modification involves incorporating a 2 mm space between the facial surface of the maxillary anterior teeth and the inner surface of the mouthguard. To evaluate its efficacy an in vitro study using finite element analysis was performed.

Aim: To evaluate the effect of mouthguard design on stress distribution pattern on anterior teeth and maxillary jaw on application of standardized horizontal forces on maxillary teeth.

Materials and Methods: This FEA study investigates stress distribution and impact absorption of conventional and modified mouthguards. A 4mm EVA mouthguard with 2mm anterior spacing was compared to a standard 4mm EVA mouthguard under impact loading.

Results: Modified mouthguard show lower stress distribution (24.06 and 17.45 MPa) compared to conventional mouthguards (34.15 and 1.26 MPa) in anterior and posterior regions respectively. In case of deformation modified mouthguard shows comparatively more deformation (0.069 and 0,062 mm) than conventional mouthguards (0.05) in anterior and posterior regions respectively.

Conclusion: Modified Mouthguard proves significantly more effective in absorbing forces, reducing stress concentration, and providing superior protection as compared to the conventional mouthguard.

Keywords: Finite Element Analysis, Mouthguard, Modified mouthguard Impact absorption, Stress distribution.

Introduction

Mouthguards play a fundamental role as protective devices, safeguarding the teeth, gums, and surrounding structures from the impact and trauma associated with sports activities. [1] The use of protective devices while sports activity is crucial as it has been reported that trauma as a result of sports activities represent up to 1/3rd of all orofacial injuries. [2] Half of these injuries constitute traumatic dental injuries, a category that can unquestionably be prevented through the diligent adoption of appropriate preventive measures. Such increasing incidences necessitates the need to educate sports teachers, children and parents regarding traumatic dental injuries and associated complications including psychological trauma. [3]

In 1981, the ASTM (American Society for Testing and Materials) issued the F697-80 standard, which set regulations that mouthguards should ideally be custom-made devices, prepared and fitted by dentists according to specific fabrication and cutting guidelines.

Custom-fitted mouthguards, crafted by dentists using Ethylene vinyl acetate (EVA) sheets of varying thickness, are precisely tailored to an individual's unique mouth structure, providing optimal and personalized protection.[4] These mouthguards contribute by absorbing and distributing impact, by reducing the force of impact on the jaws minimizing the likelihood of dental injuries such as broken or displaced teeth, lacerations to the lips or tongue, and even concussions.[5] The mechanical properties, including shock absorption, comfort, fit, and wearability of mouthguards, are influenced by factors such as the type of material, geometry, and the manufacturing process employed in their fabrication. EVA sheet meets international standards for mouthguard fabrication and has shown satisfactory performance under compressive and shear forces, as having favourable mechanical properties. [6] Though according to several authors, 4 mm appears to be the optimal thickness for adequate shock absorption [7], in certain sports like skating, injuries or sudden falls often result in impacts to the jaws and teeth from a frontal direction which can lead to a direct blow to the anterior teeth. [8] It is well-documented that maxillary central incisors are the most prone teeth to dental injury and enamel fracture the most common type of fracture [9,10]. Also from literatures, the critical areas in terms of energy absorption and transmitted forces are the incisal edges of the anterior teeth and the attached (marginal) gingiva [11] shows that there is still requirement of modifications in mouthguard which will reduce the severity of trauma. Considering this innovative mouthguard is designed with meticulous precision, maintaining a 2 mm space between the labial surface of maxillary anterior teeth and the inner surface of the mouthguard, aiming to offer athletes and individuals susceptible to oral injuries an advanced solution that prioritizes both safety and usability, ensuring a high level of wearability.

For development and validation of this innovative mouthguard design we decided to use Finite Element Analysis (FEA), a potent computational tool in engineering, empowers professionals to simulate and forecast material responses under diverse conditions. Aim of this study is to evaluate the effect of mouthguard

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design on stress distribution pattern on anterior teeth and maxillary jaw on application of standardized horizontal forces on maxillary teeth.

Materials & Methods: The fundamental principle of Finite Element Analysis (FEA) involves dividing a model into smaller finite elements, each characterized by simple geometry and interconnected by nodes (typically, 4 nodes per element). The amalgamation of these finite elements and nodes is referred to as a mesh [12].

Model designing

In the initial stage, a virtual geometry model (VGM) representing the dentoalveolar structure was generated by utilizing previously exposed cross-sectional CBCT tomography image of a 20- year- old healthy patient with normal occlusion. The Stereo-Lithography (STL) format, essential for this process, was developed from the DICOM images obtained through Computer-Aided Design (CAD) technology. The conversion from DICOM to STL was facilitated by the materialized mimics, specifically through 64-bit 0perating system, x64-based processor This software yielded a detailed 3D CAD model that comprehensively incorporated the maxillary teeth, periodontal ligament, bone support (including cortical and trabecular bone), soft tissue, and a mouthguard [Figure 1]

Subsequently, using Three-dimensional tetrahedron shape elements, a mesh network model was created from the STL files through computer-aided engineering software, namely ANSYS 19.2. This mesh model served as the foundation for conducting a structural mechanical analysis [Figure 2] The processing of the mesh model was performed through a convergence test (10%) to obtain a finite number of elements and nodes.

Upon completion of the mesh, physical properties such as Young's modulus (E), Poisson's ratio (ν), and density (d) [13] were assigned to each component within the model, including enamel, dentine, cortical bone, cancellous bone, and the mouthguard [Table 1].

Ensuring the homogeneity, isotropy, and linear elasticity of the models, they were rendered stable in the X, Y, and Z directions through the imposition of boundary conditions on the mesh model. Two distinct mouthguard configurations were devised:

1. A model depicting the maxillary jaw with a conventional mouthguard, characterized by a uniform thickness of 4mm [Figure 3 (A)]
2. An alternative model illustrating the maxillary jaw with a modified mouthguard, also possessing a thickness of 4mm. Notably, this variant introduced a 2mm space between the facial surfaces of maxillary anterior teeth and the mouthguard. [Figure 3 (B)]

Force calculation

The formula utilized to ascertain the necessary force is:

$F=M\times A$

Where:

F denotes the force required,

M represents the average weight, and

A signifies the average acceleration by which the skating player moves.

Here we used average acceleration approximately 16.7 m/s (37.38 mph) based on the comprehensive list of speed skating records ratified by the International Skating Union [14].

The upper limit of the average weight for children in the age group of 20 years is approximately 70 kg.[15] Therefore, the standard force with the higher range of weight is determined as:

Force= 70kg× 16.7m/s = 1167 N

Nodal forces similar to the impact of a sudden fall during a sporting activity were assessed on the anterior teeth on both sides, with a total magnitude of 1167N being considered. After that through the series of

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calculations and mathematical equations performed by the software, the simulation result for the parameters - stress distribution and mouthguard displacement in form of values and the von Mises stress distributions pattern in the model can be visualized using a colorimetric scale, where red colour represents the highest von Mises stress value and blue colour indicates the lowest von Mises stress value. The pictographic images were obtained through the FEA representing the stress distribution in both the models.

Results & Discussion

The stress distribution: By employing von Mises equivalent stresses, a method that consolidates all stress components into a singular equivalent stress value. The analysis of stress distribution revealed notable disparities between the modified mouthguard (MG) and the conventional mouthguard in various regions [Figure 4 A & B]. The von Mises stress values for both the modified and conventional mouthguards are presented in Table 2

Mouthguard displacement: The distances between nodes on the mouthguard and tooth model, denoted as contact separation, were calculated during the impact analysis to describe the movement of the mouthguard. The displacement value in modified and conventional mouthguard is stated in Table 3. It is important to highlight that increased displacement in modified mouthguard occurred without the transmission of stresses to the underlying teeth and bone (Figure 5 A & B) in contrast to conventional mouthguard where stress distribution directed towards the teeth, maxilla, and adjacent bony structures is observed.

Discussion

Polymers hold significant potential for mouthguard fabrication due to their excellent mechanical properties and ease of shaping at low temperatures. Additionally, various polymers can be combined with other materials to improve mechanical characteristics, offering numerous application possibilities and enhancing their properties, reproducibility, and consistency.[16]

In recent years, numerous research has been dedicated to enhance the impact absorption capabilities of mouthguards, primarily focusing on refining the materials employed. Previous studies have explored various approaches, such as the incorporating intermediate layers like sorbothane [17], and employing a hard insertion with space [18].

In the current investigation, a novel modification was implemented by introducing a mere 2 mm space between the 4mm EVA mouthguard and the facial surfaces of the anterior teeth. This specific modification yielded promising results, showcasing a reduction in transmitted forces and an augmented buffer capacity. The enhanced performance is attributed to the material's ability to flex within the space created between the mouthguard and the teeth, allowing for superior energy absorption.

This transformative quality plays a crucial role in mitigating impact forces, either by absorbing or dissipating them, ultimately leading to a notable reduction in forces transmitted to the teeth. This feature is of paramount importance as it serves to prevent potential damage or injuries to the teeth, especially in scenarios involving impacts such as those encountered in sports or other physical activities.

Unlike standard choices, this mouthguard demonstrates improved buffering capacity and superior energy transformation properties. Such modified mouthguard of recommended thickness i.e. 4 mm with incorporation of 2 mm space in between facial surfaces and mouthguard which is also easy to manufacture and to use, should recommend for use by athletes involved in various sport activities.

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Legend Tables & Figures

Table 1: Mechanical properties of the dental structure and material

Structure	Elastic modulus (MPa)	Poisson's ratio	Density (g cm^{-3})
Enamel	84100	0.30	2.14
Dentine	18600	0.30	2.97
Periodontal ligament	50	0.45	0.95
Cortical bone	13700	0.33	2.00
Cancellous bone	1400	0.31	0.70
Soft tissue	1.8	0.30	0.95
EVA	18000	0.30	0.95
Mpa- Megapascal, g cm^{-3} – Gram per cubic Centimeter			

Table 2: Stress Distribution under Traumatic Force in Mpa

Parameters	Points	Conventional MG	Modified MG
Stress Distribution in Mpa	Incisally	34.154	24.06
	Canine Labially	102.59	22.12
	Molar Buccally	1.2617	17.45
	Molar Occlusally	1.0263	4.39
Mpa- Megapascal, MG - Mouthguard			

Table 3: Mouthguard Displacement / Deformation in mm under Traumatic Force

Parameters	Point	Conventional MG	Modified MG
Deformation In mm	Anteriorly	0.05 mm	0.069mm
	Posteriorly	0.05mm	0.062mm

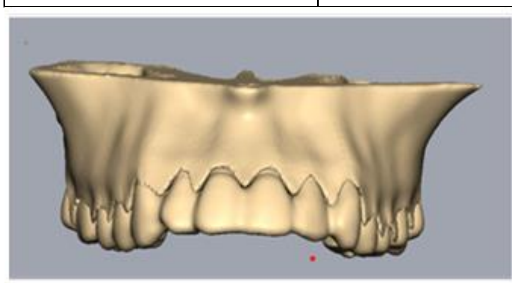

Figure 1: 3-D CAD Model Maxilla

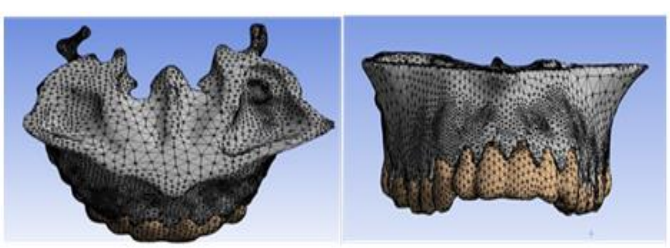

Figure 2: 3-D Tetrahedron mesh model

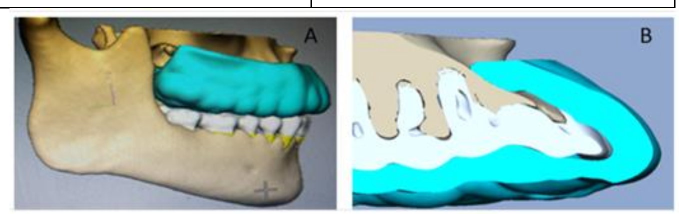

Figure 3: 3-D (A) Conventional mouthguard, (B) Modified Mouthguard with 2 mm space between facial surface of maxillary anterior teeth and mouthguard.

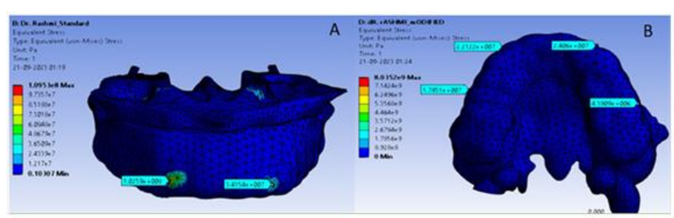

Figure 4: Stress distribution (A) Conventional mouthguard model, (B) Modified mouthguard model.

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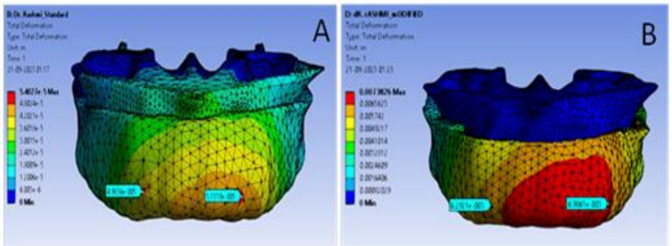

Figure 5: Mouthguard Displacement (A) Conventional mouthguard model, (B) Modified mouthguard model

Conclusions

Though 4 mm conventional mouthguard are sufficient to preventing or reducing trauma to the teeth, gingival tissue, lips and jaws, this modified mouthguard shows comparatively enhanced buffer capacity and superior energy transformation properties. The advancements in mouthguard design showcased in this innovation bear significant implications for athletes and individuals engaging in high-impact activities. This innovative approach holds promise for fostering a safer environment during physically demanding pursuits, underscoring its potential to make a meaningful impact on the well-being of those involved in such activities.

Abbreviations

CBCT- Cone Beam Computed Tomography

EVA- Ethylene Vinyl Acetate

FEA- Finite Element Analysis

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