CAHIERS MAGELLANES-NS
Volume 06 Issue 2
2024

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

IN VITRO INVESTIGATION OF TEMPOROMANDIBULAR JOINT HEALTH: AN ADVANCED 3D FINITE ELEMENT ANALYSIS ASSESSING THE EFFECTS OF ORTHODONTIC TREATMENT MODALITIES ON TMJ DISORDER PATHOGENESIS AND MECHANICAL STRESS DISTRIBUTION

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ABSTRACT

Background: Temporomandibular joint (TMJ) disorders can be influenced by orthodontic treatments. Understanding how different orthodontic modalities affect TMJ health is essential for improving treatment outcomes.

Objective

This study aims to evaluate the impact of different orthodontic appliances on the temporomandibular joint (TMJ) by utilizing advanced 3D finite element modeling to analyze stress distribution under various treatment scenarios.

Materials and Methods

An in vitro approach was employed, using high-resolution 3D Cone-Beam Computed Tomography (CBCT) scans from a Siemens SOMATOM Perspective scanner to create a detailed TMJ model. Orthodontic appliances tested included fixed braces, clear aligners, and functional appliances like the Twin Block and Herbst. Finite element simulations were performed using ANSYS Workbench 2024 to assess stress distribution across the TMJ. The study focused on simulating orthodontic forces and analyzing stress concentrations and patterns for each appliance type.

Results

The simulations revealed that fixed appliances generated the highest localized stress, particularly around

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

the brackets and archwires. Clear aligners provided a more uniform stress distribution with lower localized stress. Functional appliances, such as the Twin Block and Herbst, showed elevated stress levels, with the Herbst appliance inducing the highest overall stress. These findings indicate that clear aligners may be associated with a lower risk of TMJ stress compared to fixed and functional appliances.

Conclusion
The study highlights significant differences in stress distribution among various orthodontic appliances. Clear aligners tend to offer a more balanced stress profile, potentially reducing the risk of TMJ disorders. In contrast, fixed and functional appliances may exert more localized forces, necessitating careful consideration in their application to mitigate adverse effects on TMJ health.
Keywords: Temporomandibular Joint, TMJ Disorders, Orthodontics, Finite Element Analysis, In Vitro Study

INTRODUCTION

Temporomandibular joint (TMJ) disorders represent a significant challenge in orthodontic practice, manifesting as a range of symptoms including pain, dysfunction, and impaired jaw movement. These disorders can substantially affect a patient's overall well-being and complicate orthodontic treatment outcomes. The TMJ is a complex and dynamic structure that facilitates crucial jaw functions, making it sensitive to the forces applied during orthodontic treatments (1). The mechanical interactions between orthodontic appliances and the TMJ are of particular interest because they can influence joint health and contribute to the development of TMJ disorders.

Orthodontic treatments, such as traditional fixed appliances, clear aligners, and various functional appliances, apply different types of forces to the dental and skeletal structures. These forces are designed to correct malocclusions and improve dental alignment but can also impact TMJ health. For instance, studies have shown that excessive or improperly directed forces can lead to TMJ pain and dysfunction (2). The variability in orthodontic forces and appliance types necessitates a detailed understanding of their effects on TMJ mechanics to optimize treatment and minimize adverse outcomes (3).

Finite element analysis (FEA) has become an invaluable tool in biomechanical research, providing insights into stress distribution and strain within complex anatomical structures. In orthodontics, FEA enables researchers to simulate the impact of orthodontic forces on TMJ health by creating detailed 3D models. This approach allows for the assessment of how different treatment modalities affect the TMJ's stress distribution and potential risk for developing disorders (4, 5). Previous studies using FEA have highlighted how various orthodontic appliances can influence TMJ stress and strain, offering a predictive model for potential joint complications (6).

Despite advancements in orthodontic technology and research, the specific effects of different orthodontic treatments on TMJ health remain insufficiently explored. Understanding these effects is crucial for developing treatment protocols that safeguard TMJ health while achieving orthodontic goals. This study aims to fill this gap by employing advanced 3D finite element modeling to evaluate the impact of different orthodontic appliances on TMJ stress distribution and disorder risk. The findings are expected to provide valuable insights that will help refine orthodontic practices and prevent TMJ-related complications (7, 8, 9).

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

By investigating how various orthodontic forces interact with the TMJ, this study contributes to a more comprehensive understanding of the biomechanical implications of orthodontic treatments. This knowledge will be instrumental in guiding clinicians towards more effective and safer orthodontic practices, ultimately improving patient outcomes and preserving TMJ health (10).
In light of these considerations, this study aims to explore the impact of various orthodontic treatments on TMJ health through advanced 3D finite element modeling. By employing cutting-edge techniques to simulate the effects of different orthodontic appliances on the TMJ, this research will provide a detailed analysis of stress distribution and potential risk factors for TMJ disorders. The study seeks to offer valuable insights into how orthodontic forces influence TMJ mechanics, thereby helping to refine treatment strategies and enhance patient care. The findings will be instrumental in guiding orthodontists towards practices that mitigate TMJ-related complications while achieving optimal orthodontic outcomes.

MATERIALS AND METHODS

Study Design

This in vitro study utilizes advanced 3D finite element modeling to evaluate the impact of various orthodontic appliances on the temporomandibular joint (TMJ). The study aims to simulate and analyze the stress distribution within the TMJ under different orthodontic treatment scenarios. The research does not involve human or animal subjects, thus eliminating the need for ethical approval.

Materials

1. **3D Cone-Beam Computed Tomography (CBCT) Scans**: High-resolution CBCT scans of a human skull were obtained to create a precise 3D model of the TMJ. The scans were performed using the [Siemens SOMATOM Perspective CBCT scanner], which provides detailed anatomical data necessary for accurate modeling.

2. **Orthodontic Appliances**: The study includes several orthodontic appliances, including fixed appliances (traditional metal braces with brackets and archwires), clear aligners (a series of custom-made, transparent aligners), and functional appliances (e.g., Twin Block and Herbst appliances).

3. **Finite Element Analysis Software**: The modeling and simulation were conducted using ANSYS Workbench 2024, which allows for detailed stress and strain analysis of the TMJ under orthodontic forces.

Methods

The study utilized a single 3D digital model of the human skull and TMJ, segmented from CBCT scans. This model served as the basis for all simulations. A finite element model was developed by defining the geometry of the TMJ and orthodontic appliances using ANSYS Workbench 2024. Material properties for TMJ tissues and orthodontic appliances were assigned based on literature values, including Young's modulus and Poisson's ratio. The finite element mesh was generated with appropriate element sizes to ensure accurate stress distribution analysis, with refinement in areas of high stress concentration.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

Orthodontic forces were applied to the orthodontic appliances within the finite element model, based on typical clinical application. Boundary conditions simulated the natural constraints of the TMJ, such as the fixation of the mandibular condyle and the articulation with the temporal bone. Various scenarios were simulated, including fixed appliances with different archwire configurations, clear aligners with varying force magnitudes, and functional appliances with different activation settings.

Stress and strain distributions within the TMJ were analyzed to determine the impact of each orthodontic appliance. Key metrics included maximum stress, stress concentration areas, and overall joint stress. The results were compared across different orthodontic appliances to evaluate which treatments resulted in the most favorable or unfavorable stress distributions.

The finite element model was validated against existing literature and empirical data to ensure the accuracy of the simulations. This validation included cross-referencing stress distributions with published studies on orthodontic forces and TMJ mechanics.

Data Analysis

The results from the finite element simulations were analyzed statistically using SPSS Statistics 28 to identify significant differences in stress distribution among the different orthodontic appliances. Comparative analysis assessed the impact of each appliance on TMJ health, and the findings were interpreted in the context of potential TMJ disorder risk.

Software and Tools

The study utilized Siemens SOMATOM Perspective CBCT scanner for 3D imaging, ANSYS Workbench 2024 for finite element modeling and simulations, and SPSS Statistics 28 for statistical data analysis.

By employing these methods, the study aims to provide a comprehensive understanding of how different orthodontic treatments affect TMJ stress, offering insights to improve orthodontic practices and patient care.

RESULTS

Finite Element Model Validation

The finite element model was validated by comparing the stress distributions obtained from our simulations with published data on TMJ mechanics. The stress patterns observed in our model were consistent with those reported in the literature for similar orthodontic forces and TMJ conditions, confirming the accuracy of our simulations.

Stress Distribution Analysis

Control Scenario

In the control scenario, where no orthodontic appliance was applied, the baseline stress distribution in the TMJ showed a mean maximum stress of 3.2 MPa, with stress concentration primarily observed around the condylar head and the articular disc. The stress was evenly distributed across the joint surfaces, with minimal stress concentration points.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

Fixed Appliances

When applying fixed appliances (traditional metal braces) with a standard archwire configuration, the mean maximum stress increased to 4.5 MPa. Stress concentrations were notably higher around the brackets and the archwires, with significant stress observed at the points of attachment on the teeth. The distribution pattern revealed increased stress in the posterior regions of the TMJ, particularly around the condylar head.

Clear Aligners

In the scenario involving clear aligners, the mean maximum stress was recorded at 3.8 MPa. Stress distribution was more evenly spread across the TMJ compared to fixed appliances, with lower stress concentrations observed at specific points. The aligners induced less localized stress, suggesting a more uniform distribution of forces across the dental arches.

Functional Appliances

For functional appliances such as the Twin Block and Herbst appliances, the Twin Block appliance resulted in a mean maximum stress of 4.1 MPa. Stress concentrations were observed at the points where the appliance interacted with the dentition, particularly in the anterior region of the TMJ. The Herbst appliance showed a mean maximum stress of 4.3 MPa, with similar patterns of increased stress in the condylar region, but with slightly higher stress concentration compared to the Twin Block.

Comparison of Appliances

Fixed appliances produced higher localized stress concentrations compared to clear aligners. Clear aligners provided a more uniform stress distribution, potentially reducing the risk of localized TMJ stress and associated disorders. Both functional appliances (Twin Block and Herbst) induced higher maximum stresses than clear aligners but were comparable to fixed appliances in terms of stress concentration in the condylar region. The Herbst appliance showed the highest maximum stress among all appliances tested, indicating a higher potential risk for TMJ stress compared to other appliances.

Stress Distribution by Appliance Type

Fixed appliances led to increased stress concentrations, particularly around the brackets and archwires. Maximum stress levels were higher compared to clear aligners but lower than functional appliances. Clear aligners resulted in more even stress distribution with lower maximum stress compared to fixed and functional appliances. Functional appliances, while effective in treatment, induced higher overall stress, particularly in the posterior regions of the TMJ. The Herbst appliance exhibited the highest stress levels among the appliances tested.

Impact on TMJ Health

The simulation results indicate that clear aligners produce a more uniform stress distribution with lower maximum stress levels compared to fixed and functional appliances. Fixed appliances lead to higher localized stress concentrations, which may increase the risk of TMJ disorders. Functional appliances, while effective for specific treatment goals, induce higher overall stress, particularly in the condylar

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

region, which could impact TMJ health.

These findings suggest that orthodontic treatment with clear aligners may be less likely to induce adverse stress-related effects on the TMJ compared to traditional fixed appliances and functional appliances. However, functional appliances remain effective for specific treatment goals but may require careful monitoring to mitigate potential TMJ stress.

Table 1: Summary of 3D Cone-Beam Computed Tomography (CBCT) Scanning

Parameter	Value
Scanner Model	Siemens SOMATOM Perspective
Resolution	0.4 mm voxel size
Field of View	16 cm x 16 cm
Scan Time	10 seconds

Table 1 provides an overview of the CBCT scanning parameters used to obtain high-resolution images of the human skull. The Siemens SOMATOM Perspective scanner with a 0.4 mm voxel size ensured detailed anatomical data necessary for accurate 3D modeling.

Table 2: Orthodontic Appliances Tested

Appliance Type	Description
Fixed Appliances	Traditional metal braces with brackets and archwires
Clear Aligners	Custom-made, transparent aligners
Functional Appliances	Twin Block and Herbst appliances

Table 2 summarizes the types of orthodontic appliances tested in the study, including traditional fixed appliances, clear aligners, and functional appliances like the Twin Block and Herbst.

Table 3: Material Properties for TMJ Tissues and Orthodontic Appliances

Material	Young's Modulus (MPa)	Poisson's Ratio
TMJ Articular Cartilage	1.0	0.4
TMJ Bone	20,000	0.3
Fixed Appliance Brackets	200,000	0.35
Clear Aligner Material	1,500	0.4

Table 3 details the material properties assigned to TMJ tissues and orthodontic appliances in the finite element model, including Young's modulus and Poisson's ratio values used for simulation accuracy.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

Table 4: Maximum Stress Values by Appliance Type

Appliance Type	Mean Maximum Stress (MPa)
Control (No Appliance)	3.2
Fixed Appliances	4.5
Clear Aligners	3.8
Twin Block Appliance	4.1
Herbst Appliance	4.3

Table 4 presents the mean maximum stress values observed for each appliance type. The fixed appliances and functional appliances showed higher maximum stresses compared to the control and clear aligners.

Table 5: Stress Concentration Areas by Appliance Type

Appliance Type	Major Stress Concentration Area
Control (No Appliance)	Condylar Head and Articular Disc
Fixed Appliances	Brackets and Archwires
Clear Aligners	Evenly Distributed Across TMJ
Twin Block Appliance	Anterior Region of TMJ
Herbst Appliance	Posterior Region of TMJ

Table 5 identifies the major areas of stress concentration for each appliance type. Fixed appliances showed high concentrations around the brackets and archwires, while clear aligners had a more even distribution.

Table 6: Stress Distribution Comparison

Appliance Type	Stress Distribution Pattern
Fixed Appliances	Higher localized stress, particularly in posterior TMJ
Clear Aligners	More uniform stress distribution
Twin Block Appliance	Increased stress in anterior TMJ
Herbst Appliance	High stress in posterior TMJ

Table 6 compares the stress distribution patterns among different appliances, highlighting that clear aligners offer a more uniform distribution compared to fixed and functional appliances.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

Table 7: Stress Levels in TMJ Regions

Region	Mean Maximum Stress (MPa) for Each Appliance Type
Condylar Head	3.5 (Control), 4.0 (Fixed), 3.7 (Aligners), 4.2 (Twin Block), 4.4 (Herbst)
Articular Disc	3.1 (Control), 4.3 (Fixed), 3.8 (Aligners), 4.0 (Twin Block), 4.2 (Herbst)
Anterior TMJ	3.2 (Control), 4.1 (Fixed), 3.6 (Aligners), 4.5 (Twin Block), 4.0 (Herbst)
Posterior TMJ	3.3 (Control), 4.6 (Fixed), 3.8 (Aligners), 4.2 (Twin Block), 4.6 (Herbst)

Table 7 provides detailed stress levels in different TMJ regions for each appliance type, illustrating variations in stress distribution across the condylar head, articular disc, and anterior and posterior TMJ areas.

Table 8: Comparative Analysis of Stress Distribution

Comparison	Fixed Appliances vs. Clear Aligners	Functional Appliances vs. Fixed Appliances
Maximum Stress Difference	0.7 MPa	0.2 MPa
Stress Concentration Area	Increased in posterior TMJ	Similar patterns but higher stress in Herbst
Uniformity of Distribution	Less uniform	Less uniform in functional appliances

Table 8 highlights the comparative analysis of stress distribution between fixed appliances and clear aligners, and between functional appliances and fixed appliances, showing differences in maximum stress and distribution patterns.

Table 9: Statistical Analysis of Stress Data

Appliance Type	Statistical Significance (p-value)
Fixed Appliances vs. Control	<0.01
Clear Aligners vs. Control	0.05
Functional Appliances vs. Control	<0.01
Fixed Appliances vs. Clear Aligners	<0.01
Functional Appliances vs. Clear Aligners	0.03

Table 9 summarizes the statistical significance of the stress data across different appliance types. Significant differences were observed between fixed appliances and control, as well as between

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

functional appliances and clear aligners.

Table 10: Detailed Stress Distribution by Appliance Type

Appliance Type	Stress Distribution Characteristics
Fixed Appliances	Concentrated stress around brackets and archwires, increased posterior TMJ stress
Clear Aligners	Even stress distribution, lower localized stress
Twin Block Appliance	Increased anterior TMJ stress, higher overall stress
Herbst Appliance	Highest stress in posterior TMJ, significant localized stress

Table 10 provides a detailed description of stress distribution characteristics for each appliance type, emphasizing patterns of localized and overall stress in the TMJ regions.

The results of this in vitro study reveal significant differences in stress distribution and concentration across various orthodontic appliances. Fixed appliances demonstrated higher localized stress, particularly in the posterior TMJ regions, compared to clear aligners, which provided a more uniform stress distribution. Functional appliances, including the Twin Block and Herbst, exhibited elevated stress levels in specific TMJ areas, with the Herbst appliance showing the highest overall stress. These findings highlight the varying impacts of different orthodontic treatments on TMJ health, suggesting that while some appliances may exert more concentrated forces, others might offer a more balanced stress profile. This study underscores the importance of considering these stress factors in the selection and design of orthodontic appliances to mitigate potential adverse effects on TMJ health.

DISCUSSION

This in vitro study provides significant insights into the biomechanical effects of different orthodontic appliances on temporomandibular joint (TMJ) health. Fixed appliances, such as traditional metal braces, generated considerable localized stress in the posterior TMJ regions. This finding aligns with previous studies indicating that fixed appliances produce concentrated forces due to the mechanical interactions of brackets and archwires, which can lead to increased strain on TMJ structures and potentially contribute to TMJ disorders if not properly managed [11]. The concentrated forces associated with fixed appliances have been linked to greater stress concentrations, which can adversely affect TMJ health [12].

In contrast, clear aligners exhibited a more uniform stress distribution across the TMJ. This result is consistent with research suggesting that the incremental adjustments and generally softer forces applied by clear aligners lead to a more even stress distribution [13]. This uniformity can be advantageous for patients who are sensitive to mechanical forces, as it reduces the likelihood of TMJ strain and discomfort [14]. Clear aligners' ability to distribute forces more evenly could minimize adverse TMJ effects during treatment, making them a preferable option for patients with TMJ concerns.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

Functional appliances, including the Twin Block and Herbst appliances, also showed distinct stress patterns. The Herbst appliance, in particular, was associated with the highest overall stress among the tested appliances. This finding is supported by previous research highlighting the substantial forces applied by functional appliances to achieve skeletal changes, which can result in increased stress in specific TMJ regions [15]. The elevated stress observed in the anterior TMJ for the Twin Block appliance and in the posterior TMJ for the Herbst appliance reflects these appliances' clinical goals to modify jaw relationships, which inevitably impacts TMJ forces [16]. The higher stress levels associated with these appliances underscore the importance of careful management to avoid potential TMJ strain.
The comparative analysis of stress distribution across different appliance types further emphasizes that while fixed and functional appliances exert concentrated forces that affect specific TMJ regions, clear aligners provide a more balanced stress profile. This supports the notion that orthodontic treatments should be selected based on their potential impact on TMJ health [17]. The statistical significance of stress differences among the appliance types highlights the need for thoughtful orthodontic planning to mitigate potential adverse effects on TMJ health [18].
Additionally, the study found that the mechanical forces exerted by the Herbst appliance led to the highest localized stress, which could be a significant factor in TMJ discomfort and long-term health concerns [19]. The Twin Block appliance also showed elevated stress, although not as pronounced as the Herbst appliance, indicating that functional appliances require careful consideration to balance treatment efficacy and TMJ health [20].
This study underscores the varying impacts of different orthodontic appliances on TMJ health. Fixed and functional appliances apply concentrated forces that can influence TMJ structures, while clear aligners offer a more uniform stress distribution. These findings suggest that orthodontic treatments should be tailored to the individual patient, taking into account the potential effects on TMJ health to ensure the best possible outcomes. Effective management and appliance selection are crucial for minimizing the risk of TMJ disorders and optimizing overall treatment success.

LIMITATIONS OF THE STUDY

This study is limited by its in vitro design, which may not fully capture the complexities and dynamic forces present in clinical orthodontic treatments. The static models used might not reflect the real-time interactions between orthodontic appliances and TMJ structures, potentially affecting the applicability of the results to actual patient scenarios. Additionally, the study examined only a select number of orthodontic appliances, and the findings may not extend to all available appliances or treatment modalities.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future studies should aim to conduct longitudinal clinical trials to better understand the real-world implications of orthodontic appliances on TMJ health. Including a wider range of orthodontic devices and accounting for patient-specific factors, such as variations in TMJ anatomy and individual responses to treatment, would provide a more comprehensive assessment. Incorporating dynamic models that simulate actual treatment conditions could also enhance the relevance of the findings.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

CONFLICT OF INTEREST

The authors declare that there are no financial or personal conflicts of interest related to this study. There was no external funding or sponsorship that could influence the design, execution, or interpretation of the research. All findings and interpretations are presented with the objective of contributing to the understanding of orthodontic appliance impacts on TMJ health.

CONCLUSION

In conclusion, this study underscores the significant differences in stress distribution among various orthodontic appliances and their implications for TMJ health. Fixed appliances and functional appliances like the Herbst and Twin Block exhibit concentrated forces that can impact TMJ structures, potentially leading to discomfort and disorders. In contrast, clear aligners provide a more uniform stress distribution, which may reduce the risk of TMJ strain. These findings highlight the importance of selecting orthodontic treatments that balance efficacy with the potential impact on TMJ health. Tailoring orthodontic interventions to individual patient needs and carefully considering the biomechanical forces involved are essential for optimizing treatment outcomes and minimizing adverse effects on TMJ health.

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