From Linear to Viscoelastic Model of Mandible: A Paradigm Shift in FEM Study

Prajakta Khade, Amit Ajmera

Abstract: ***The clinical effectiveness and stress exerted by orthodontic appliances to the bone needs to be analysed because the loading force produces strain in the soft tissue matrix which is responsible for bone remodelling. Finite element analysis stimulates complex biologic structures and their bio-mechanical behaviours under different conditions and various forces in orthodontics for many decades. Using finite element analysis many researchers attempted to show stress and strain distribution in maxilla, the mandible generated by orthodontic appliances such as expanders, Class II correctors, face-masks and temporary anchorage devices. Despite all advancement , the clinical effects of the appliances where studied on a linear set of elastic material properties to stimulate behaviours of viscoelastic bone tissue. With elastic models, it is impossible to calculate displacements of the bone over a period of time, but it is crucial for when the study of orthodontic appliance like fixed functional appliance is carried out. While a viscoelastic model expresses changes over time. In this study, we aimed to compare the structural behaviours of a viscoelastic model of the mandible with forsus appliance in action with those of linear elastic model of mandible.***

Keywords: finite element analysis, fixed functional appliances, viscoelastic model, linear elastic model

1. Introduction

The clinical effectiveness and the stress exerted by the orthodontic appliance to the bone needs to be analyzed because the loading applied to the bone through the corresponding strain in the soft tissue matrix is responsible for bone remodeling. Throughout the years, many approaches, such as brittle lacquer, photoelasticity, and holography have been used to study the effects of orthodontic force on bones.

In 1984, Williams et al first used finite element analysis as a tool to study the center of rotation of maxillary incisors in relation to elastic properties of the periodontal ligament. Finite element analysis (FEA) simulates complex biologic structures and their biomechanical behaviors under different conditions and various forces in orthodontics for many decades. Using FEA many researchers attempted to show stress and strain distributions on the maxilla and mandible generated by orthodontics appliances such as expanders, Class II correctors, facemasks, and temporary anchorages devices.

Despite all major advancements in the field, most previous studies examining the clinical effects of orthodontic appliances employed a set of linear elastic material properties to simulate behaviors of viscoelastic bone tissue. With elastic models, it is impossible to calculate displacements of the bone over a long period of treatment time, which is crucial for studying the end results of orthodontic appliances; an elastic model can only express instantaneous behaviors of the bone. In contrast, a viscoelastic model visualizes long term, time dependent stress and strain pattern in the mandible after being exposed to orthopedic forces. A viscoelastic model expresses changes over time.

In this study, we aimed to compare structural behaviors of a viscoelastic model of the mandible with forsus appliance in action with those of a linear elastic model of the mandible.

2. Materials and Methods

The study was carried out to compare structural behaviors of viscoelastic model of mandible with forsus appliance in action with those of linear elastic model.

So for that, CBCT scan of 11 years old boy with the retrognathic mandible was taken. Sequential CT images were acquired at 2mm intervals in the axial direction parallel to the Frankfort plane.

A 3D CAD model (Fig1) was developed employing Mimics software. Mimics software assists in transporting the data, envisions and aids in 3D interpretation and calculating the CT scan details. CT scan images processed utilizing Mimics software, were then transported into a stereo- lithography model. The obtained CAD model was used to construct the geometric model of the tooth in Geomagic Modelling Software. This Scanned Data was then imported into Altair HyperMesh Software. Imported Data was CAD Model used for this FE Simulation. Files in stereo-lithography format were converted into FEM model. The FEM is composed of an aggregate of small elements that are sufficient to describe the geometry of the subjects. This is called creating the mesh or meshing (Fig2). The software used for geometric modeling was Altair HyperWorks.

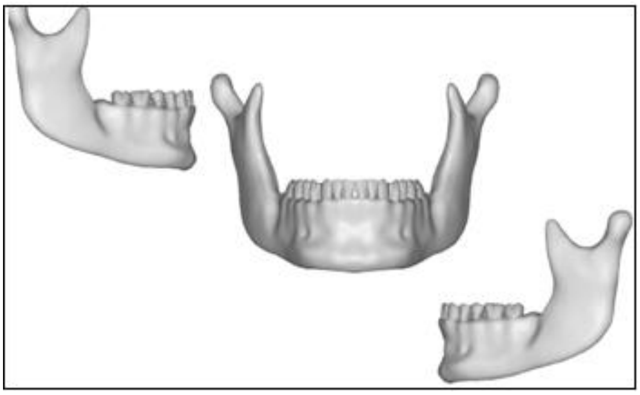


Figure 1: Generation of CAD Model

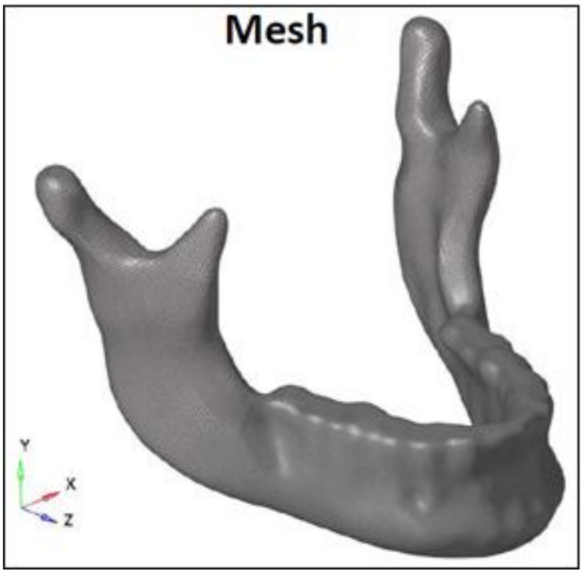


Figure 2: Meshing

Meshing:

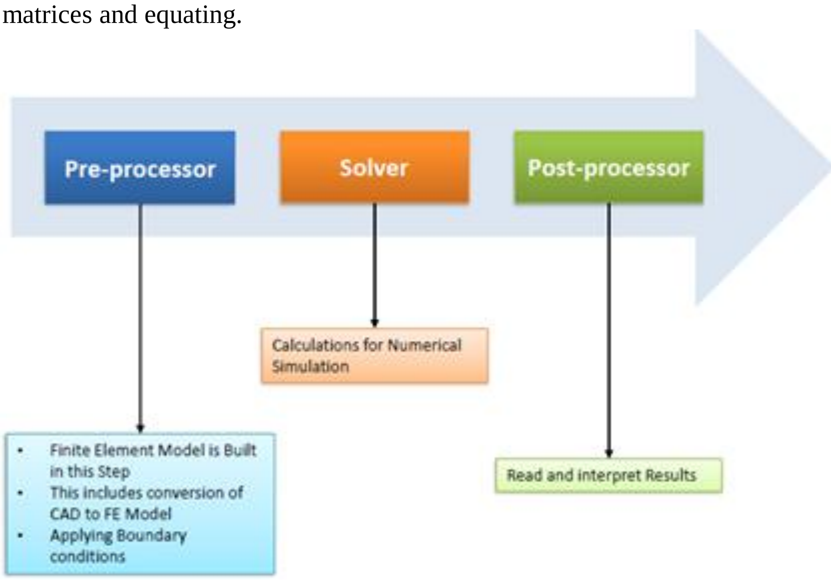
Subdivide i.e. discretize the complex geometry into suitable set of smaller elements of finite dimepoints connecting two or more elements are called as nodes or nodsions (2D OR 3D). The corner nodes are called as external node while the additional nodes which occur on the sides of elements are called as secondary external nodes.

Meshing Details

Node and Element Count

Component	No. of Nodes	No. of Elements
Mandible	105636	556217

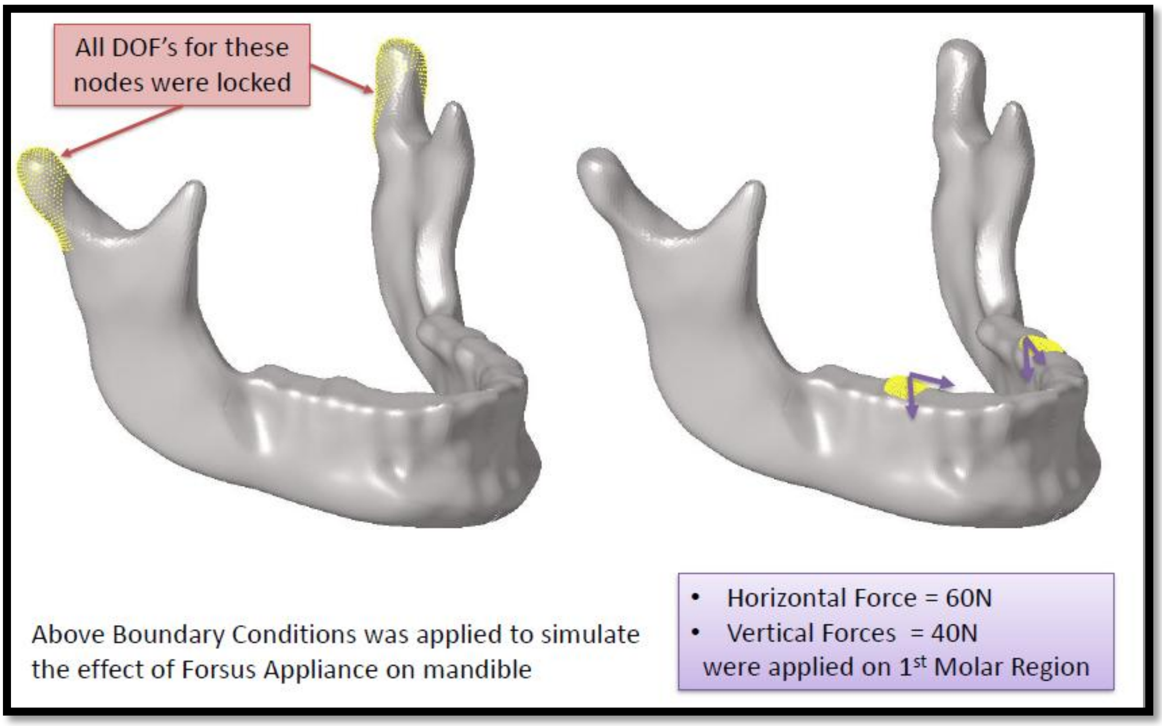
Essential Steps in FEM:
- Select the type of analysis.
- Discretization.
- Develop the element matrices and equating.
- Imposition of boundary status
- Application of load.
- Post processing of results.

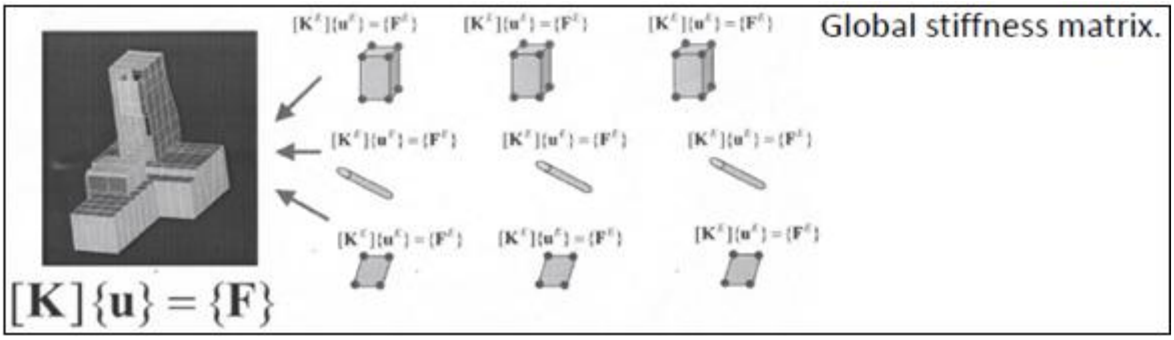


Material Properties
Maxwell model was selected for mandible in this FE stimulation. Further, to stimulate viscoelastic behaviour of mandible for a period of 50mins Prony Series Material Mode was selected. A simple sketch of a Viscoelastic Material Model – Maxwell is as shown below. This is specified time period. 50 mins here represents treatment period of 6months.

Component	Young Modulus (MPa)	Poisson's Ratio (µ)	Tau (Prony Series) (*T*)
Mandible	13700	0.3	50mins

Boundary Conditions:





$$[K]\{u\} = \{F\} \Rightarrow \{u\} = [k]^{-1}\{F\}$$

K = Stiffness matrix; u = Deflection; F = Force

Figure 3: A.) Elastic modeling displacement. Symphysis area exhibits 0.092 mm of displacement. B) Viscoelastic modeling displacements. The symphysis area exhibits a displacement of approximately 2.422 mm

Calculations

The FE Model was submitted to Altair RADIOSS software for finite element calculation. We specified material properties to the elements and obtained algebraic equation defining stiffness for each element. Stiffness matrix (K) will relate the forces acting on the structure and displacement resulting from these forces in following manner.

Displacement at a node has to be same for all adjacent elements. Combine element matrices to obtain one master equation called Global stiffness matrix.

3. Results

Post- processing was done in Altair HyperView software.

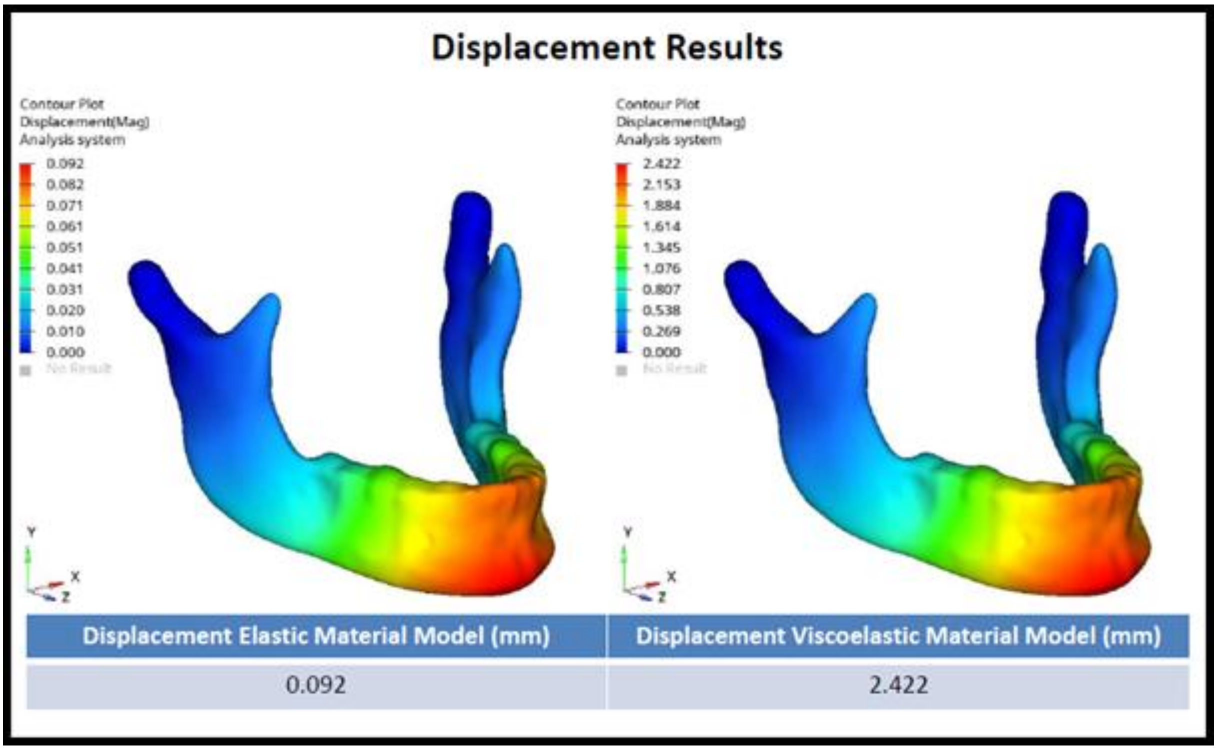
In both models, we study principal stresses, von Mises stresses, and the magnitude of_displacement of the mandible when loaded with forsus appliance.

Fig 3 A and B shows the magnitude of displacements when the elastic and viscoelastic material properties were incorporated.
Various colors in different areas represent the range of their corresponding displacements; red indicates an instant and maximum displacement, and blue indicates minimum displacements. The FEM analysis revealed that the maximum displacement resulted from the Herbst appliance in the elastic model was 0.04 mm at the chin in a forward and downward direction.

In fig 4 and 5 the von Mises stresses in both elastic and viscoelastic models respectively. The colors represent different ranges of stress values in various regions (ie, red for the maximum and blue for the minimum values). FEM analysis exhibits the areas of stress in the mandible immediately after force applications. The stress patterns were more concentrated at the buccal ramus areas and around the first molars.

Fig 5and 6 showed the results of maximum principal stresses when elastic and viscoelastic material properties were used.

Although the amount of force should remain constant during treatment, there appears stress relaxation in the areas (as stress receded from the origin of loading). At the beginning and end of treatment, stressed areas accumulated in the condylar neck and the alveolar bone around posterior teeth.



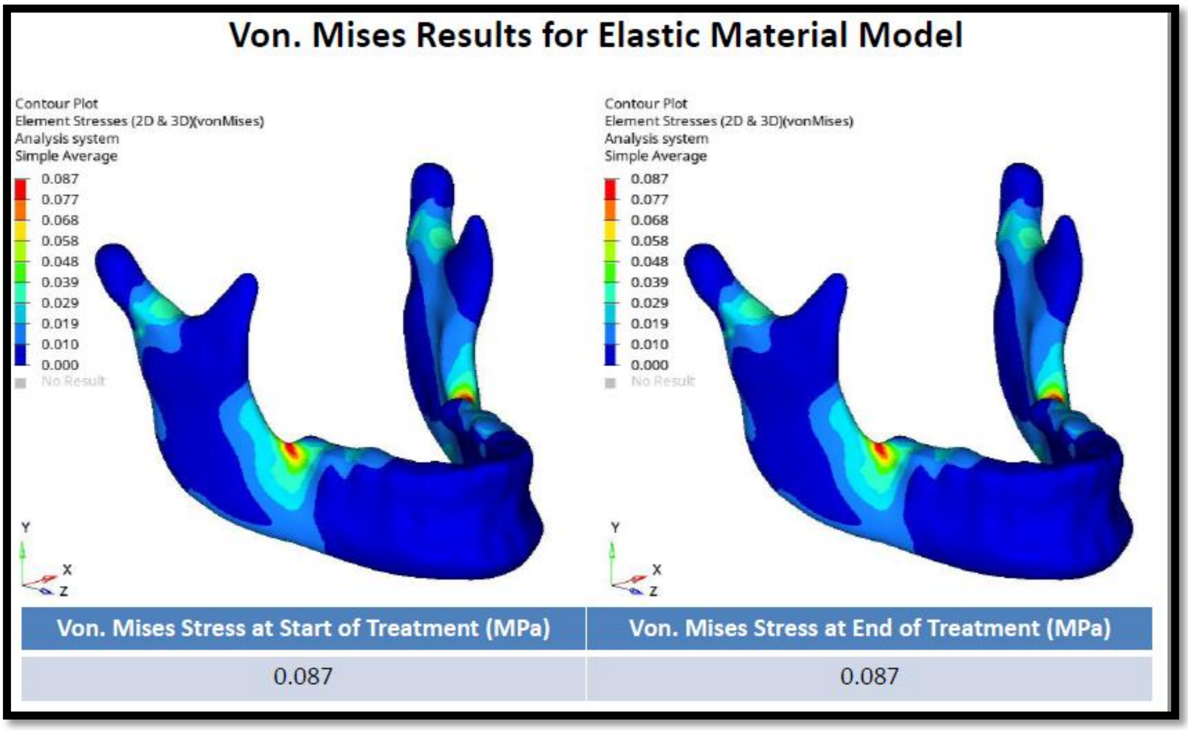


Figure 4: Elastic models for von Mises stress. A) Von Mises stresses at the beginning of the treatment B) Von Mises stresses at the end of treatment

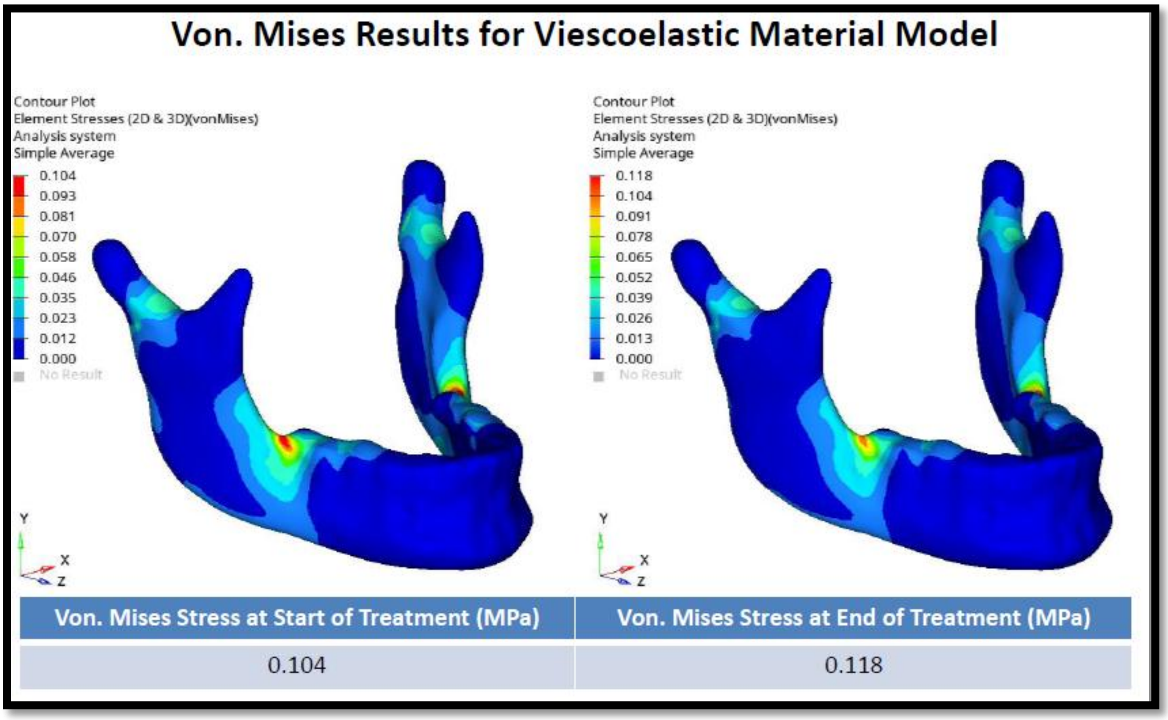


Figure 5: Viscoelastic models for von Mises stress. A) Von Mises stresses at the beginning of the treatment B) Von Mises stresses at the end of treatment.

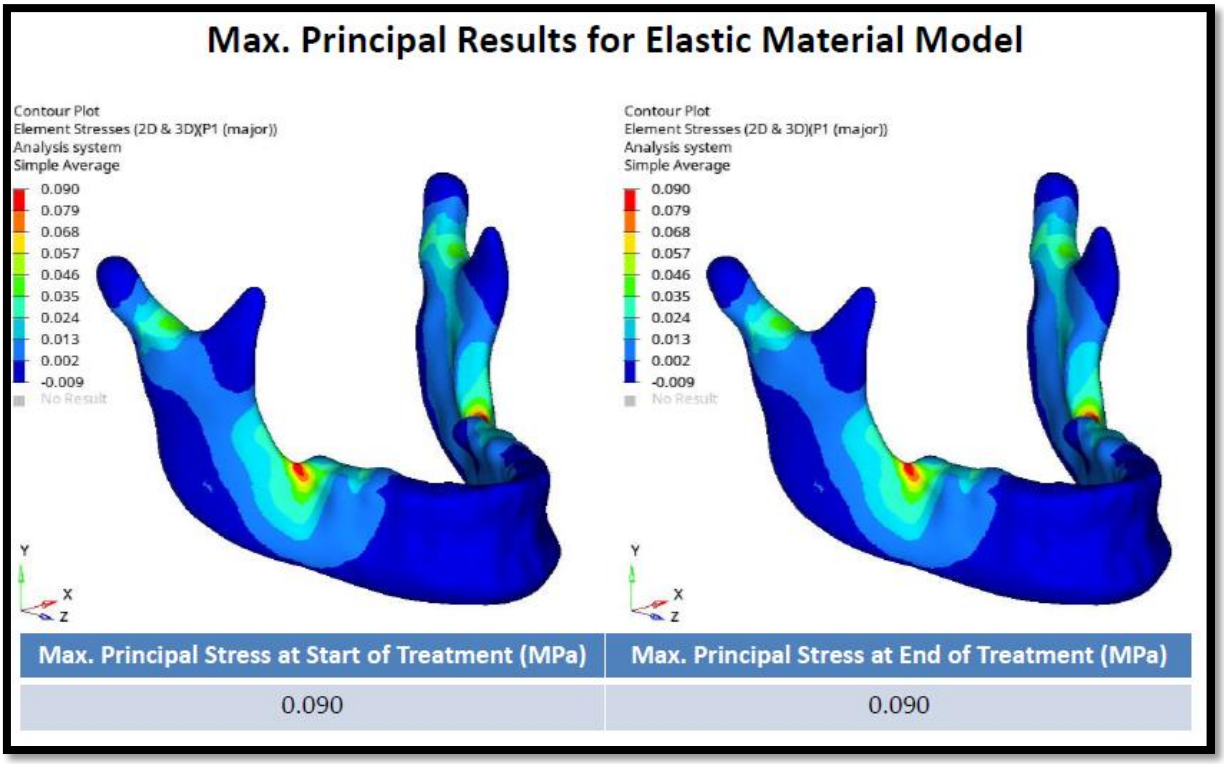


Figure 6: Elastic models for Maximum principal stress. A) Maximum principal stresses at the beginning of the treatment B) Maximum principal stresses at the end of treatment in megapascals (MPa).

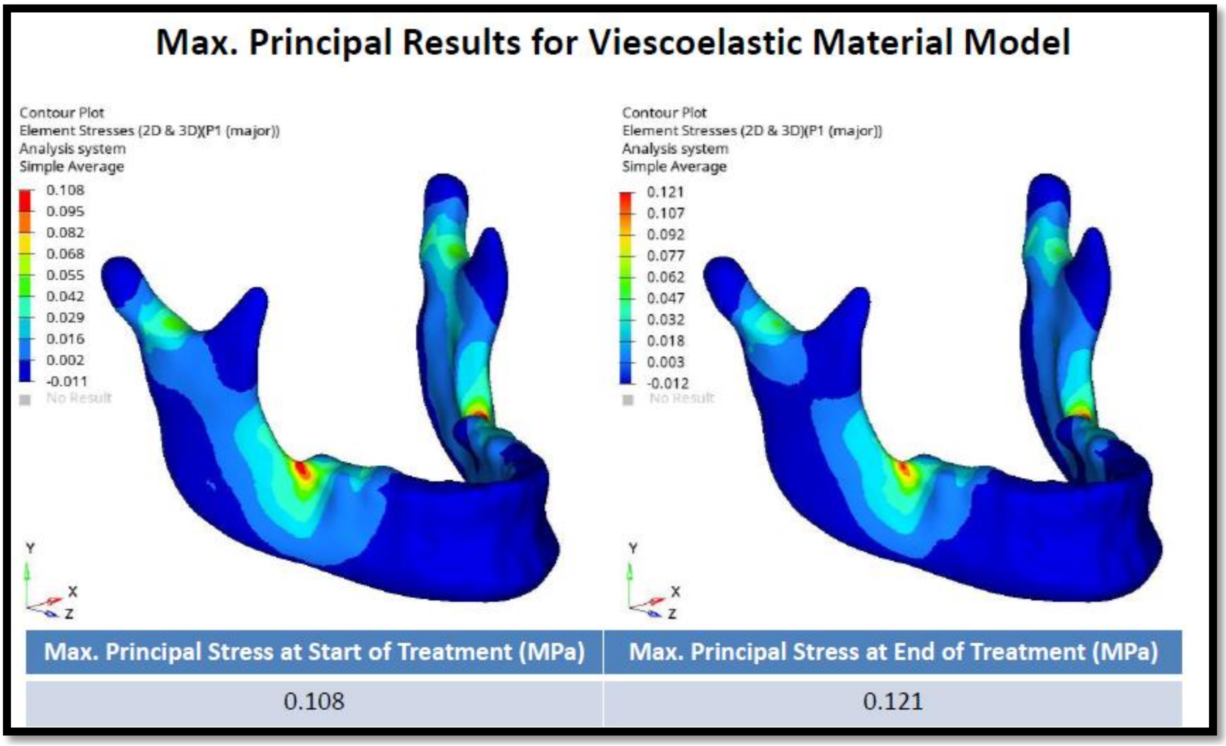


Figure 7: Viscoelastic models for Maximum principal stress. A) Maximum principal stresses at the beginning of the treatment B) Maximum principal stresses at the end of treatment in megapascals (MPa)

4. Discussion

	Viscoelastic Material Model		Elastic Material Model	
	Von. Mises Stress (MPa)	Max. Principle Stress (MPa)	Von. Mises Stress (MPa)	Max. Principle Stress (MPa)
At Start of Treatment	0.102	0.108	0.087	0.09
At End of Treatment	0.118	0.121	0.087	0.09
Difference %	13%	12%	0%	0%

- It's observed that in elastic material model stress is same at the start and end of the treatment. This is because it does not capture the time aspect of force application. Linear elastic model only calculates and reports stress and displacements instantaneously at the time of application of force. Displacements are very small in elastic model and thus they do not represent actual clinical scenario.
- Stress in viscoelastic material model is increasing by about 12% from start to end of the treatment. This is because the continuous application of load for the defined period. That is the way mandible behaves when forsus is applied.

	At Start of Treatment	
	Von. Mises Stress (MPa)	Max. Principle Stress (MPa)
Elastic Material Model	0.087	0.09
Viscoelastic Model	0.104	0.108
Difference %	20%	20%

The fundamental drawbacks of modeling bone as an elastic material are as follows:

1) Elastic modeling only provides instantaneous stress and displacement magnitudes at the time of applying forces to the model. Thus, the actual behavior of the bone over time cannot be examined;
2) Results of the elastic model do not simulate clinical outcomes because values indicating instantaneous displacement are invariably very small as shown in this study.

- We offered more clinically acceptable models with viscoelastic elements showing more clinically relevant mechanical properties of the mandible
- Forsus appliance in the models exhibited a downward and forward displacement of the mandible as the condyles immobilized in the condylar sockets.
- Pancherz et al. found that the chin was displaced anteriorly and inferiorly by 1.9-3.1 mm.
- In our viscoelastic model, we assumed the treatment with forsus appliance was 6 months, and the amount of force exerted by the appliance was constant.

- As a result, our model achieved 2.422 mm of displacement anteriorly and inferiorly at the chin point at the end of treatment.
- In contrast, the value of displacement that our elastic model achieved was 0.092 mm.

5. Conclusion

- The objective of this study was to introduce a viscoelastic FE analysis of the mandible and to examine if the viscoelastic model may yield more clinically compatible outcomes.
- This study validates that viscoelastic models of the bone are superior and more clinically relevant than elastic models for FEM analysis in our field.
- The downward and forward displacement of the chin point of 2.422 mm appears to be empirical, but ought to inevitably be hypothetical because this magnitude is based on 1 mandible and several given boundary conditions.
- Nonetheless, this report opens a door for further studies.

References

[1] Pancherz H, Bjerklin K, Hashemi K. Late adult skeletofacial growth after adolescent Herbst therapy: a 32-year longitudinal follow-up study. American Journal of Orthodontics and Dentofacial Orthopedics. 2015 Jan 1;147(1):19-28.
[2] Chaudhry A, Sidhu MS, Chaudhary G, Grover S, Chaudhry N, Kaushik A. Evaluation of stress changes in the mandible with a fixed functional appliance: a finite element study. American Journal of Orthodontics and Dentofacial Orthopedics. 2015 Feb 1;147(2):226-34.
[3] Park SW, Schapery R. Methods of interconversion between linear viscoelastic material functions. Part I—A numerical method based on Prony series. International journal of solids and structures. 1999 Apr 1;36(11):1653-75.
[4] Wu Z, Ovaert TC, Niebur GL. Viscoelastic properties of human cortical bone tissue depend on gender and elastic modulus. Journal of Orthopaedic Research. 2012 May;30(5):693-9.
[5] Kim DG, Huja SS, Lee HR, Tee BC, Hueni S. Relationships of viscosity with contact hardness and modulus of bone matrix measured by nanoindentation.
[6] Zadi ZH, Bidhendi AJ, Shariati A, Pae EK. A clinically friendly viscoelastic finite element analysis model of the mandible with Herbst appliance. American journal of orthodontics and dentofacial orthopedics. 2021 Aug 1;160(2):215-20.