ORIGINAL ARTICLE

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A clinically friendly viscoelastic finite element analysis model of the mandible with Herbst appliance

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Introduction: As a powerful numerical approximation tool, finite element analysis (FEA) has been widely used to predict stress and strain distributions in facial bones generated by orthodontic appliances. Previous FEA models were constructed on the basis of a linear elastic phase of the bone response (eg, elastic bone strains to loading). However, what is more useful for clinical understanding would be predicting long-term strains and displacements of bone-segments responding to loading, yet tissue responses are (1) not promptly observable and (2) hard to predict in nature. **Methods:** Viscoelastic property of the mandibular bone was incorporated into FEA models to visualize long-term, time-dependent stress and strain patterns in the mandible after being exposed to orthopedic stress. A mandible under loading by a Herbst appliance was modeled, and outcomes of the constructed elastic and viscoelastic models were compared. **Results:** Patterns and magnitudes of the displacement throughout the mandible predicted by the viscoelastic model were exhibited in accordance with previous clinical outcomes of Herbst appliance therapy. The elastic models exhibited similar displacement patterns; however, the magnitude of the displacements in the models was invariably small (approximately 1 per 100) compared with those outputs of corresponding viscoelastic models. The corresponding maximum stress level in our viscoelastic mandible subjected to the Herbst appliance with the same loading was considerably low and relaxed in various regions when compared with the elastic model. **Conclusions:** We suggest that a viscoelastic model of the mandible mimics our general prediction of orthopedic treatment outcomes better than those by elastic models. (Am J Orthod Dentofacial Orthop 2021;160:215-20)

To measure the clinical effectiveness of an orthodontic appliance, 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 over time.[1,2] Throughout the years, many approaches, such as brittle lacquer, photoelasticity, and holography,[3] have been used to study the effects of orthodontic force on bones. Finite element analysis (FEA) simulates complex biologic structures and their biomechanical behaviors under different conditions, and various forces were used in orthodontics for many decades. In 1984, Williams et al[4] first used FEA as a tool to study the center of rotation of maxillary incisors in relation to elastic properties of the periodontal ligament. However, owing to a lack of reports on material properties and oversimplified geometries, most studies using FEA were remote from clinical applications. Using FEA, many researchers attempted to show stress and strain distributions on the maxilla and mandible generated by orthodontics appliances such as expanders[5] to Class II correctors,[6,7] facemasks,[8-10] and temporary anchorages devices.[11]

As studies using FEA gain popularity in the orthodontic field, we note that the validity of their research relies on the soundness of input data. Therefore, defining proper material properties, accuracy in geometry, applicable forces, and boundary conditions, as well as types of analysis depending on the nature of the problem, are crucial for the soundness of a model. Digital Imaging and Communications in Medicine files converted from 3-dimensional (3D) cone-beam computed tomography

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(CBCT) images can conveniently be exported to an FEA software package, which enables researchers to build individual models to test.

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 showing nonlinear behaviors.[12,13] 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. In addition, the propagation of stress and its resultants in the bone during the treatment process cannot be captured in an elastic model because, in general, an elastic model can only express instantaneous behaviors of the bone. In contrast, a viscoelastic model factors a time-effect into account.[13] Thus, a viscoelastic model express changes over time. In this study, we aimed to compare structural behaviors of a viscoelastic model of the mandible with Herbst appliance in action compared with those of a linear elastic model of the mandible. Herbst appliances were chosen because there are ample clinical data which would help examine and understand the results of this study.[14,15]

MATERIAL AND METHODS

Briefly, the captured geometry of a mandible from CBCT in Digital Imaging and Communications in Medicine image was converted to a stereolithography (STL) file. Then, the file was transformed into a 3D computer-aided design model that can be interpreted by Finite element method (FEM) software (Abaqus; Dassault Systemes Simulia Corp, Providence, RI) for analysis. The geometry was then discretized (meshed), and material properties (such as elastic or viscoelastic) were assigned, and then finally, the applied forces from the appliance as well as the boundary conditions were specified.

A full volume CBCT image on a boy aged 10 years with skeletal Class II was used. The CBCT was taken with CareStream CS9300 (Carestream Health, Rochester, New York, NY) at the following settings: 90 kVp; 5 mA; exposure time of 8 seconds; resolution of 180 micrometer. The Ma 4. Invivo software (Anatomage, San Jose, Calif) was used to derive the file in STL format. The STL files were then transferred to Abaqus, which is a FEA software package with pre- and postprocessing capabilities. Using the 3D image obtained from the CBCT, the geometry was imported and meshed using other modules of Abaqus. Material properties[16]—namely, Young modulus (or modulus of elasticity) and Poisson ratio—were assigned in accordance with the values in the Table.

Table. Material properties of the mandible

Modulus of elasticity (E)	*Material properties of cortical bone*	
	Poisson ratio (υ)	*Retardation period (τ)*
13,700 MPa	0.3	50 min

For viscoelastic models, the Prony series parameters were chosen for the study because the material behaves close to the Maxwell model.[17] The retardation period was assumed to be 50 minutes,[18] and the treatment period was assumed to be 4300 hours, which approximates 6 months. Although the Kelvin-Voigt model is usually used in the literature to capture the viscoelastic behavior of the cortical bone, it appears reasonable for clinical orthodontic treatments to assume that the cortical bone shows significant plastic behavior as well.[19] This behavior in the cortical bone is often observed and suggested by researchers in biomechanical engineering.[20]

After defining the material properties, the boundary conditions were imposed as the translational lock in all the global directions for elements on the condylar heads of the mandible, as shown in Figure 1. To study the deformation of the mandible, degrees of freedom (ie, movement of the node in 1 or more directions x, y, and z) must be restricted to avoid rigid body motion. Such constraints are termed as boundary conditions. In addition, a static force of 40 N in the vertical and 60 N in the horizontal direction was imposed through masticatory muscles to the first molar regions on the mandible

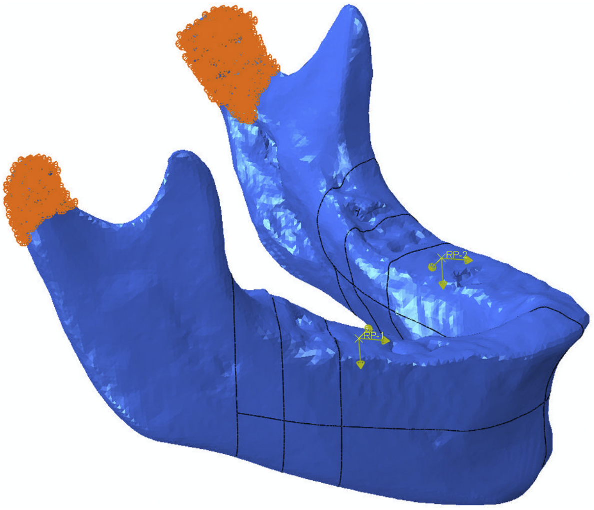

Fig 1. Boundary conditions applied to the areas in orange color on the condylar heads. *Arrows* in *yellow* indicate the directions of force applied.

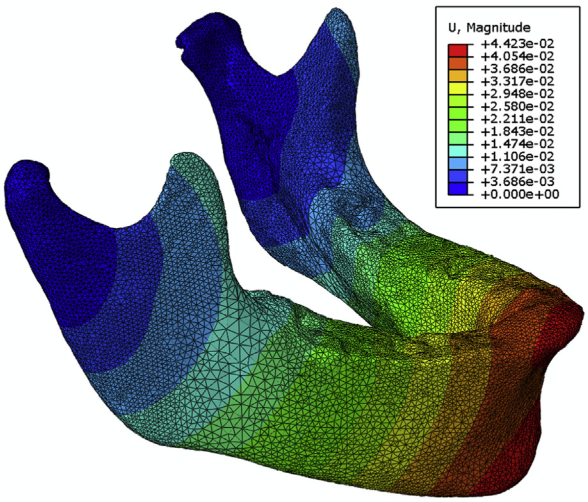

Fig 2. Elastic modeling displacement. The symphysis area exhibits a displacement of approximately 0.04 mm.

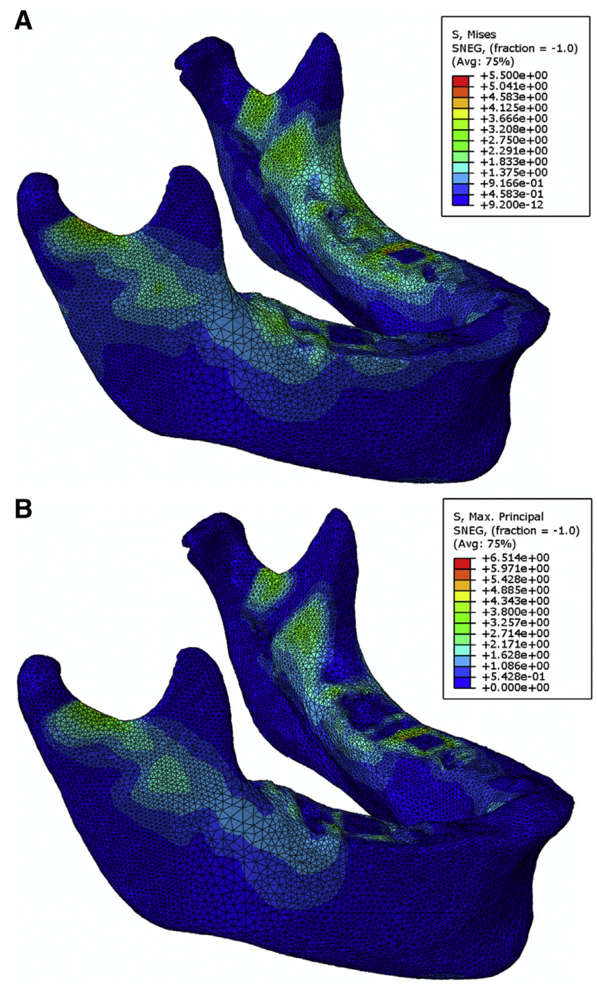

Fig 3. Elastic model: **A,** shows von Mises stress contour; **B,** shows Maximum principal stress contour. Colormaps are in megapascals (MPa).

to simulate the loading from the Herbst appliance. These forces were adopted from the average bite-force, and the forces from the masticatory muscles reported previously in the literature.[16,21]

A pair of models using 2 separate material properties were constructed and analyzed. For 1 model, the elastic properties of the cortical bone were incorporated for the immediate elastic response. To account for the time parameter, the identical model except for viscoelastic material properties was constructed and analyzed. One of the purposes of this phase was to see the progression of how stresses and strains emerge and propagate through the course of treatment during Herbst appliance treatment. In addition, the magnitude of displacement, as well as the change in stress levels due to creep, were of interest in this study. In the postprocessing phase (which is the last phase of an FEA study), we observed the results of applied forces in the form of displacements and stress distributions. These results were visualized by contour maps in colored magnitudes of the outputs. One should note that the value of the displacement obtained from our elastic model could be very small because of the high elastic modulus of the cortical bone that we adopted. In addition, the elastic response would reflect a transitory spontaneous behavior of the mandible because creep or stress relaxation were not a part of the interpretation.

RESULTS

In both models, we exhibit principal stresses, von Mises stresses, and the magnitude of each displacement. von Mises stress was calculated to predict yielding of the bone.[22,23] The total number of nodes employed for the model was 26,260, along with the total number of elements of 52,235.

Figure 2 shows the magnitude of displacements when the elastic 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.

Figures 3, *A* and *B* show the von Mises model and the maximum principal stresses, 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 areas of lighter green color indicating the highest stresses in our elastic model were approximately 1.8-3.6 MPa for von Mises and 2.2-4.3 MPa for maximum principal stresses. The stress patterns were more concentrated at the buccal and lingual ramus areas and around the first molars.

Figure 4 shows the results of stresses and displacements when a visco-analysis with viscoelastic material properties were used. In this model, the maximum magnitude of displacement (in red color) at the chin and the alveolar bone area for incisors was approximately 3.1 mm. (See Video, available at www.ajodo.org) for dynamic visualization of the achieved theoretical displacement over 6 months.

In Figure 5, each panel represents the stresses distributed in the viscoelastic model immediately after the loading begins (*A* and *C*) and at the end of the assumed treatment period (*B* and *D*). One can observe that the areas under high stress (green areas) were reduced in size and more localized over time. Note that areas covered in green were reduced in *B* and *D* compared with *A* and *C*. 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, as shown in Figure 5.

DISCUSSION

The treatment effects expressed in the mandible by functional appliances have long been analyzed clinically using cephalometric images based on statistics. Being a

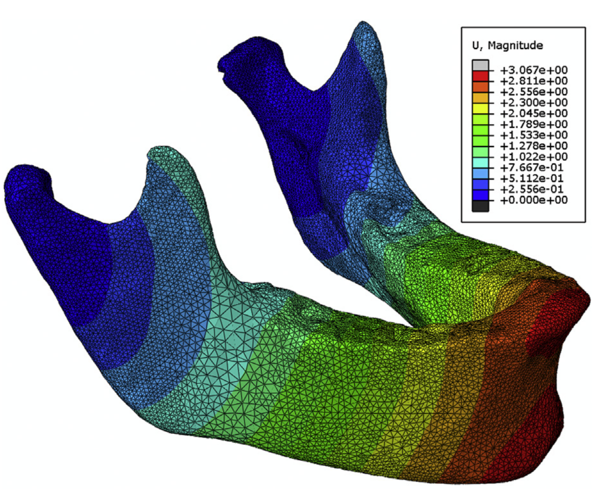

Fig 4. Viscoelastic modeling displacement. The symphysis area exhibits a displacement of approximately 3.067 mm. See the Video (available at www.ajodo.org) for animation.

clinical study, the longitudinal cephalometric analysis takes time and provides study results only after completion of the course of treatment. The accuracy of the cephalometric approach relies on the number of subjects participating in the study. Furthermore, the cephalometric analysis only measures a mixture of displacement and growth at the end of the treatment, which offers a prediction of the treatment effects.

In contrast, FEA is an objective tool that can attest to the mechanical effect (independent of growth effects) of the functional appliances associated with the shape and size of anatomic structures immediately. The majority of the FEM studies to date have modeled the mandible or maxilla as an elastic material.[5-7,24-27] However, as briefed earlier, it may only make sense to model the bone as a viscoelastic material.[20,28] 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; and (2) results of the elastic model does not simulate clinical outcomes because values indicating instantaneous displacement are invariably very small as shown in this study.

In this article, we offered more clinically acceptable models with viscoelastic elements showing more clinically relevant mechanical properties of the mandible. To test the practicality of our method, we chose to simulate the effects of a Herbst appliance on the mandible. The rationale behind this decision was the abundance of Herbst-based clinical studies for the Herbst appliance had been widely accepted as a Class II functional therapeutic tool. This study compared the elastic and viscoelastic FEA results and validated the magnitude of displacement approximates their corresponding clinical values expected from Herbst appliance therapy. The results of this comparison substantiate why the field should begin incorporating the viscoelastic properties of the bone for FEA models.

Our Herbst appliance in the models exhibited a downward and forward displacement of the mandible as the condyles immobilized in the condylar sockets. This outcome, serendipitously, follows the results demonstrated in the majority of previous publications that studied Herbst appliance clinically. For instance, Pancherz et al[29,30] found that the chin was displaced anteriorly and inferiorly by 1.9-3.1 mm. In our viscoelastic model, we assumed the treatment with Herbst was 6 months, and the amount of force exerted by the appliance was constant. As a result, our model achieved 3.1 mm of displacement anteriorly and inferiorly at the chin point at the end of treatment. In contrast, the value

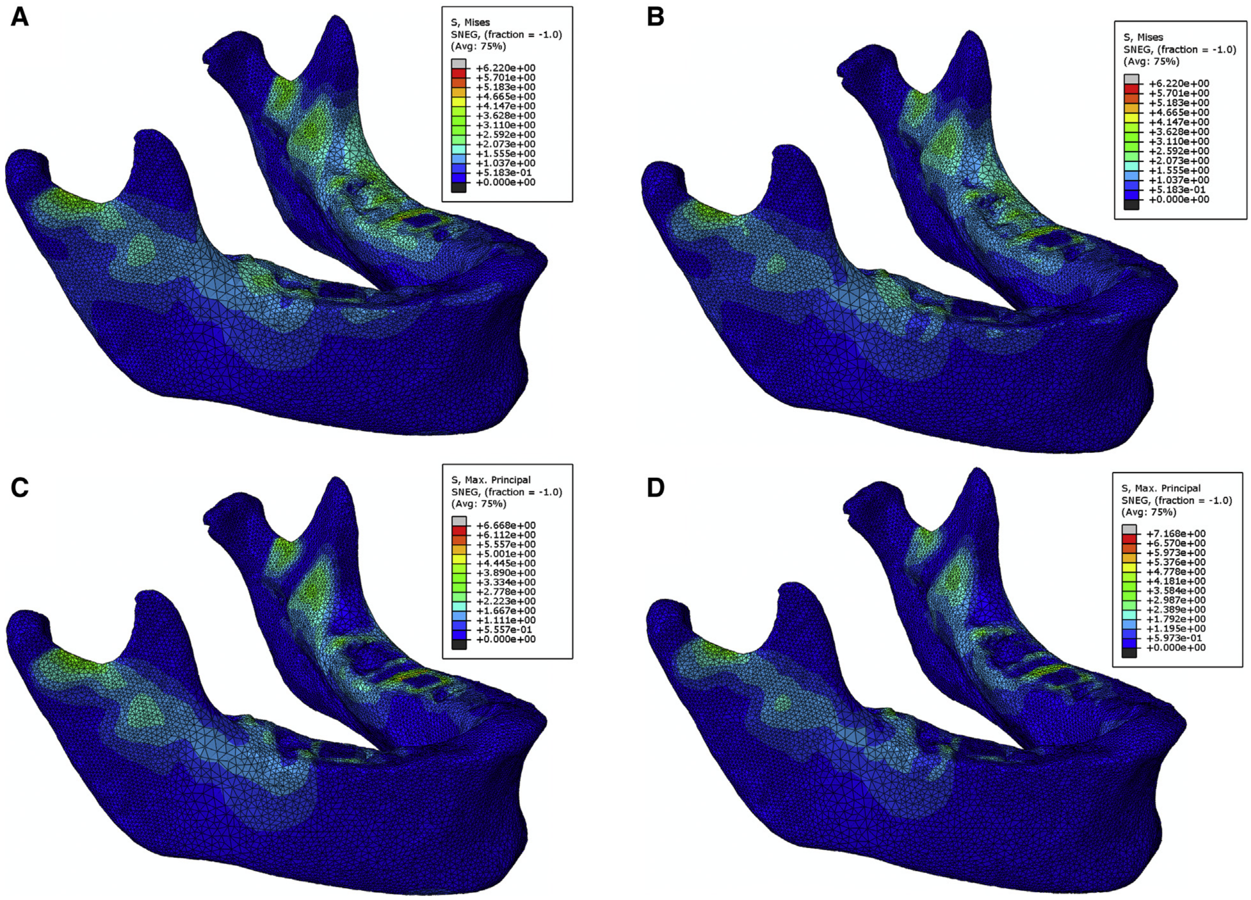

Fig 5. Viscoelastic models for von Mises stress and Maximum principal stress. Each panel indicates: **A,** von Mises stresses at the beginning of treatment; **B,** von Mises stresses at the end of treatment; **C,** maximum principal stresses at the beginning of treatment; **D,** maximum principal stresses at the end of treatment. Colormaps are in megapascals (MPa).

of displacement that our elastic model achieved was 0.044 mm.

CONCLUSIONS

The objective of this study was to introduce a viscoelastic FEA analysis of the mandible and to examine if the viscoelastic model may yield more clinically compatible outcomes. Results from our viscoelastic model demonstrated that Herbst appliance results in a downward and forward chin displacement if the patient uses the appliance for 6 months (see Video for animation, available at www.ajodo.org). Although this modeling effect does not represent a real result of growth modification, this FEA model using viscoelastic elements visualizes an average clinical outcome. A time-independent elastic model cannot demonstrate this displacement effect. This study validates that viscoelastic models of the bone are superior and more clinically relevant than elastic models for FEM analysis in our field.

A viscoelastic model should provide a better mathematical interpretation representing an outcome of the orthopedic effects of orthodontic appliances. This claim may be somewhat preposterous because we did not provide any statistical evidence for the magnitude of displacement. The downward and forward displacement of the chin point of 3.1 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 in a de novo direction. Examining the reliability of an FEA model constructed with viscoelastic elements maybe 1 example for such future studies, and testing whether the initial shape of a mandible could affect expected results of orthopedic appliances could be another.

SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ajodo.2020.04.017.

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APPENDIX

MATHEMATICAL IDEALIZATIONS AND SIMPLIFICATIONS

Viscoelasticity is the property of materials showing both viscous and elastic behavior when undergoing deformation. Viscous materials strain continuously with time when stress is applied to them, whereas elastic materials show strain when they are stretched, and as soon as the stress is released, they return to their original form.[1] Stress relaxation and creep phenomena are 2 important properties of viscoelastic materials.[2]

To model the behavior of materials, mathematical idealizations and simplifications are essential. For instance, in the elastic materials, the elasticity can be demonstrated as shown in the Supplementary Figure in which E is the modulus of elasticity, and σ is the stress. This model shows that the rate of displacement (strain) is the same as the force, but as soon as the force is removed, the spring recoils to its original shape. Viscosity or plasticity can be shown as in Supplementary Figure in which σ is the stress that is applied to the dashpot, and η is the viscosity. This model shows that as the forces are applied, the dashpot opens (get displaced), and once the forces are removed, it will stay in that position. It is good to note that the speed of displacement is controlled by the amount of force and η.

Different mathematical idealizations models such as Maxwell, Kelvin-Voigt, and standard linear solid model can be used to predict and simulate the viscoelastic material response under different loading conditions. As shown in Supplementary Figure, the behavior of viscoelastic materials is idealized using combinations of springs and dampers. The elastic part is characterized using a spring and the viscosity part by a damper (dashpot) with the properties and behaviors that are already explained. This combination can be in series and in parallel. Each component in the series has equal forces, whereas each component of a parallel system has a similar displacement. Two of the most popular combinations that have been used to describe the behavior of bone are the Voigt and Maxwell models, which are shown in Supplementary Figures, *C* and *D*, respectively. The Maxwell model, which is shown below in Supplementary Figure *C* is a damper and a spring in series. This model shows that the applied force on the spring and dashpot is equal; however, when the force is removed, the spring recoils, but the dashpot does not. Under initial displacement (strain), this model allows for gradual stress relaxation while under constant loading, gradual displacement occurs—a phenomenon that is also known as creep.[2] The other model that is very well known and used to capture the behavior of biological materials such as bone is Kelvin-Voigt model in which a damper and a spring are acting in parallel. In this model, the force is more in the dashpot initially until it is open fully, then it is maximum in the spring. It is good to note that generalized models such as the standard linear solid model (see Supplementary Fig *E*) and generalized Maxwell models are used to capture materials viscoelastic behavior as well.

In our study, we hypothesized to use the Prony parameters according to the Maxwell model to allow both stress relaxation and creep behavior. This choice was made on the basis of the intuition that in the clinical setting, we can observe relatively large displacements even by applying small forces during a long period. The Maxwell model was chosen for modeling the viscoelastic behavior of the mandibular bone. In addition, recent studies have shown plastic properties for bone in line with our current assumption.[3]

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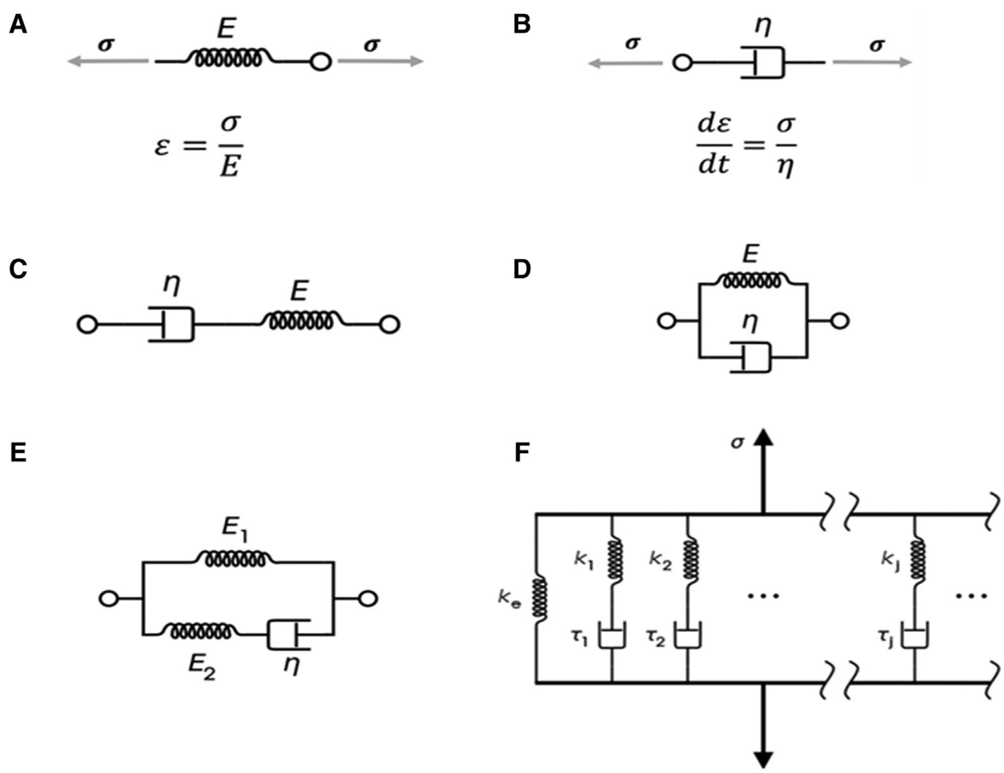

Supplementary Fig. Constitutive models of linear viscoelasticity: **A,** spring; **B,** damper (dashpot); **C,** Maxwell model; **D,** Kelvin-Voight model; **E,** standard solid model; **F,** generalized Maxwell model.