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# Towards a viscoelastic model for the unfused midpalatal suture: Development and validation using the midsagittal suture in New Zealand white Rabbits

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ABSTRACT

Maxillary expansion treatment is a commonly used procedure by orthodontists to widen a patient's upper jaw. As this is typically performed in adolescent patients, the midpalatal suture, connective tissue adjoining the two maxilla halves, remains unfused. Studies that have investigated patient response to expansion treatment, generally through finite element analysis, have considered this suture to behave in a linear elastic manner or it was left vacant. The purpose of the study presented here was to develop a model that could represent the midpalatal suture's viscoelastic behavior. Quasilinear viscoelastic, modified superposition, Schapery's, and Burgers modeling approaches were all considered. Raw data from a previously published study using New Zealand White Rabbits was utilized for model parameter estimation and validation. In this study, Sentalloy® coil springs at load levels of 0.49 N (50 g), 0.98 N (100 g), and 1.96 N (200 g) were used to widen the midsagittal suture of live rabbits over a period of 6 weeks. Evaluation was based on a models ability to represent experimental data well over all three load sets. Ideally, a single set of model constants could be used to represent data over all loads tested. Upon completion of the analysis it was found that the modified superposition method was able to replicate experimental data within one standard deviation of the means using a single set of constants for all loads. Future work should focus on model improvement as well as prediction of treatment outcomes.


## 1. Introduction

Maxillary expansion (ME), or widening of the upper jaw, is a procedure used to increase palatal width in adolescent patients via insertion of an appliance into the patient's maxilla (Bell, 1982; Haas, 1961). An active element in the appliance then generates expansion by applying outwardly directed transverse forces to the palate. Fig. 1 shows a typical appliance inserted in the upper jaw.

Predicting patient response to ME has become a topic of interest, especially through use of finite element analysis (FEA) (Lee et al., 2009; Provatidis et al., 2006, 2007). In adolescents the midpalatal suture will exist as soft connective tissue, at least for the most part, and behaves as a viscoelastic material (Herring, 2008). Yet, authors in FEA studies have assumed that the suture behaves in a linear elastic manner or they have removed it completely from the analysis (Romanyk et al., (2013)). Modeling the suture as a viscoelastic material would allow for improved fidelity of time-dependent simulations.

Viscoelastic modeling of the suture in available literature is sparse. Tanaka et al. (2000) used a Kelvin model to describe stress–strain behavior of the interparietal suture in rats, which was then incorporated into a FEA model of suture and surrounding parietal bone. Provatidis et al. (2006, 2007) developed a 'pseudo-viscoelastic' whole-skull FEA model whereby expansion loads were applied in steps, and the residual stresses were forced to zero at the beginning of each load-step. While these approaches are steps in the right direction, there is more work that may be done to improve suture modeling. Utilization of more physically representative spring/damper models or advanced nonlinear approaches may provide a better fit to experimental data and should be explored.

The primary goal of this study was to conduct preliminary work towards development of an accurate viscoelastic model for the human midpalatal suture. Four viscoelastic models were evaluated: Burgers, quasilinear viscoelastic (QLV), modified superposition (MST), and Schapery's model. These models were selected based

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on their nonlinear description (QLV, MST, and Schapery's models) or because of the physically representative spring/damper configuration (Burgers model). Model parameter determination and validation were accomplished using displacement-time data, at a constant force, from the literature for the midsagittal suture in juvenile New Zealand White Rabbits. It was hypothesized, and justified in the following discussion, that the midsagittal suture would behave in a similar manner to the midpalatal suture.

## 2. Methodology

### 2.1. Modeling methods

In a first attempt at the detailed modeling of the sutures' viscoelastic behavior, literature was consulted to identify relevant existing modeling methods. A total of four methods were selected for evaluation in their current form. Upon identifying a suitable model for predicting suture behavior, future work will focus on altering the chosen model to include specific phenomena (e.g. permanent deformation).

#### 2.1.1. QLV Model

One popular way to model the behavior of soft tissues is the quasi-linear viscoelastic (QLV) method proposed by Fung (Fung, 1993a):

$$\varepsilon(t) = \int_0^t J'(t-\tau)\frac{d\varepsilon^{(e)}[\sigma(\tau)]}{d\sigma}\frac{d\sigma}{d\tau}d\tau \tag{1}$$

where $J'(t)$ is the reduced creep function and $\varepsilon^{(e)}(\sigma)$ is the elastic response. In a study by Yoo et al. (2011), creep behavior of bovine extraocular muscles was studied using the QLV method and the following reduced creep function:

$$J'(t) = C_1 t + \frac{C_2 \sinh(C_3 t) - C_4 \cosh(C_3 t)}{C_5 \exp(C_6 t)} + C_7 \tag{2}$$

where $C_1$–$C_7$ represent model constants to be determined experimentally. Substituting (2) into (1) and using a step-input for the stress, with a magnitude of $\sigma_0$, the QLV creep formulation explored in this study is given as:

$$\varepsilon(t) = \sigma_0 J'(t) = \sigma_0\left[C_1 t + \frac{C_2 \sinh(C_3 t)}{C_5 \exp(C_6 t)} - \frac{C_4 \cosh(C_3 t)}{C_5 \exp(C_6 t)} + C_7\right] \tag{3}$$

#### 2.1.2. MST model

The MST approach is similar to the QLV model with the exception that the MST model considers the creep function inseparable (Findley et al., 1976a):

$$\varepsilon(\sigma, t) = \int_0^t J[t-\tau, \sigma(\tau)]\frac{d\sigma(\tau)}{d\tau}d\tau \tag{4}$$

Delgadillo et al. (2012) used the MST method to model creep of asphalt binders and proposed the following formulation:

$$\varepsilon(\sigma, t) = \sum_{i=1}^{n} k_i t^{m_i}\sigma^{p_i} \tag{5}$$

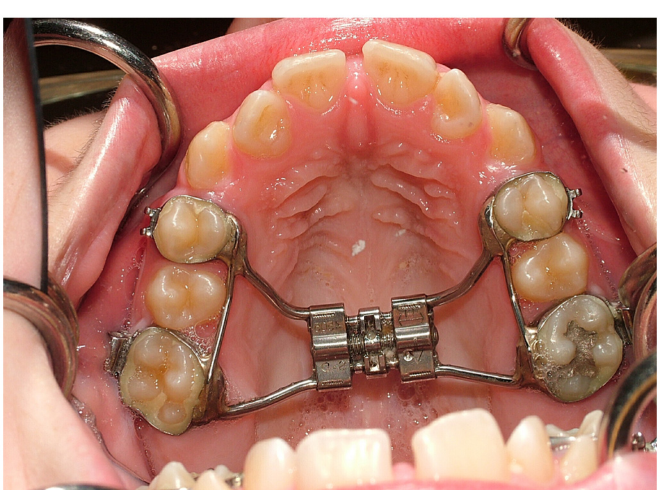

**Fig. 1.** Typical ME appliance inserted in a patient's upper jaw.

where $k_i$, $m_i$, and $p_i$ are model constants. If (5) is expanded to $n=2$, and $\sigma$ is set to $\sigma_0$, then the resulting creep formulation is given as

$$\varepsilon(\sigma, t) = \sigma_0 J(\sigma, t) = C_1 t^{C_2}\sigma_0^{C_3} + C_4 t^{C_5}\sigma_0^{C_6} \tag{6}$$

$C_1$ to $C_6$ represent model coefficients to be determined using experimental data. While asphalt binders are not necessarily related to suture tissue, it is the goal of this study to investigate a variety of viscoelastic models with different qualities, hence its selection.

#### 2.1.3. Schapery's method

Schapery's method is a viscoelastic model based on thermodynamic principles (Schapery, 1966; Findley et al., 1976b), given as:

$$\varepsilon(t) = g_0 D_0 \sigma(t) + g_1\int_0^t \varphi(\xi_\sigma - \xi_\sigma')\frac{dg_2\sigma(\tau)}{d\tau}d\tau \tag{7}$$

$$\xi_\sigma = \int_0^t \frac{ds}{a_\sigma[\sigma(s)]} \tag{7.1}$$

$$\xi_\sigma' = \int_0^\tau \frac{ds}{a_\sigma[\sigma(s)]} \tag{7.2}$$

where, in general, $g_0$, $g_1$, $g_2$, and $a_\sigma$ are functions of stress, $D_0$ is the time-independent compliance, and $\varphi(t)$ is the creep compliance. Derombise et al. (2011) considered creep of aramid fibers using an adaptation of Schapery's method. Even though aramid fibers differ greatly from suture tissue, the modeling approach used by Derombise et al. (2011) is of interest for a general exploration of viscoelastic models. These authors considered irreversible strain in their study; however, this is not a phenomenon that will be considered for the suture at this point. As such, the applicable portion of their creep model reduces to

$$\varepsilon(t) = C_1\sigma_0 + C_2\sigma_0\log_{10}(t+1) \tag{8}$$

$$C_1 = g_0 D_0 \tag{8.1}$$

$$C_2 = g_2 D_1 \tag{8.2}$$

where $D_1$ represents creep rate.

#### 2.1.4. Burgers model

While there are a variety of spring/damper formulations used to model viscoelastic materials (Fung, 1993b; Findley et al., 1976c), the Burgers model with constant coefficients was deemed most suitable for preliminary analysis. It was selected due to its instantaneous elastic response, viscous flow, and delayed elasticity; furthermore, it can also model permanent deformation. While permanent strain will not be considered in this study, it is important for future work. The Burgers model is a four-parameter configuration which consists of two springs and dampers as shown in Fig. 2. The governing equation and subsequent creep formulation for the model are given as follows:

$$\sigma + \left(\frac{C_2}{C_1} + \frac{C_2}{C_3} + \frac{C_4}{C_3}\right)\dot{\sigma} + \frac{C_2 C_4}{C_1 C_3}\ddot{\sigma} = C_2\dot{\varepsilon} + \frac{C_2 C_4}{C_3}\ddot{\varepsilon} \tag{9}$$

$$\varepsilon(t) = \sigma_0\left\{\frac{1}{C_1} + \frac{t}{C_2} + \frac{1}{C_3}\left[1 - \exp\left(\frac{-C_3}{C_4}t\right)\right]\right\} \tag{10}$$

where $C_1$–$C_4$ are all constant values.

### 2.2. Experimental data

As sufficient experimental data for the midpalatal suture in humans or other animals was unavailable to the authors, raw data from Liu et al. (2011) for the midsagittal suture (Fig. 3) in New Zealand White Rabbits was used. Sutures were exposed to a nearly constant force magnitude through Sentalloy® coil springs (GAC International, Bohemia, NY) at levels of 0.49 N (50 g), 0.98 N (100 g), and 1.96 N

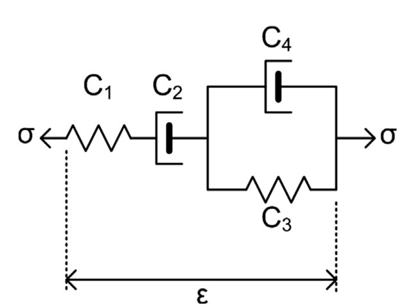


**Fig. 2.** Spring/damper configuration of the four-parameter Burgers model.