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On the Influence of Mechanical Behavior of the Middle Ear Ligaments: a Finite Element Analysis

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Summary

The interest in finite element method (FEM) concerning biomechanics has been increasing, in particular, to analyze the mechanical behavior of the human ear. In this work, a finite element model of the middle ear was made. A dynamic study based on a structural response to harmonic vibrations, for different sound pressure levels, applied on the eardrum, is presented using the ABAQUS program. The model includes different ligaments and muscle tendons with elastic and hyperelastic behavior of these supportive structure. The non-linear behavior of the ligaments and muscle tendons was considered, being the connection between ossicles done by contact formulation. Harmonic responses of the umbo and stapes footplate displacements, from 100 Hz to 10 kHz, were obtained and compared with previous published works. The traction of ligaments (superior and anterior of malleus and superior and posterior of incus) was analyzed with a focus on their importance from a structural point of view. The results of this work allow to emphasize the importance on the use of hyperelastic models to simulate the mechanical behavior for the ligaments and tendons.

keywords: biomechanics, finite element method, middle ear, elastic, hyperelastic.

Introduction

To analyze the mechanical behavior of the human middle ear, some studies have been developed and published (Prendergast *et al.* 1999; Sun *et al.* 2002; Koike *et al.* 2002; Gan *et al.* 2004). However, to obtain more realistic results, some improvements in numerical simulation models are needed.

In this sense, a finite element model of the middle ear is shown in the present work. For this purpose and based in imagiology data, the study starts with the construction of a 3D solid model of the ossicles and eardrum, for a normal ear. The discretization of these components is made using tetrahedral solid elements for the ossicles and hexahedral for the eardrum. The model also includes the ligaments, muscles and respective tendons and a simulation of the cochlear fluid.

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For the ossicles and eardrum the mechanical properties considered are available in literature (Prendergast *et al.* 1999; Sun *et al.* 2002; Gan *et al.* 2004). The connection between ossicles is done using contact formulation, which can be interpreted as a simulation of the capsular ligaments (Gentil *et al.* 2007). The numerical simulation was performed with the ABAQUS program (ABAQUS 2007).

As the most important audible frequency range is located from 125 Hz to 8 kHz (usually used in audiogram) the dynamic study achieved in this work is centered between 100 Hz to 10 kHz.

Considering the umbo and stapes footplate displacements, a dynamic study based on a structural response to harmonic vibrations is presented and the results are compared with published works (Kurokawa *et al.* 1995; Nishihara *et al.* 1996; Huber *et al.* 1997; Prendergast *et al.* 1999; Gan *et al.* 2004; Lee *et al.* 2006). Usually, the works based on the finite element method use a linear elastic material model for the supportive structures of the middle ear (Prendergast *et al.* 1999; Sun *et al.* 2002; Elkhouri *et al.* 2006; Koike *et al.* 2002). However, as it was recently showed by Cheng and Gan the correct mechanical behavior of ligaments and muscle tendons is non-linear (Cheng and Gan 2007). From the mechanical point of view, this non-linearity can be treated with one hyperelastic model (Wang *et al.* 2007) for the anterior maleolar ligament, stapedius and tensor tympani tendons). In the present work the hyperelastic constitutive model of Yeoh is used for all ligaments and muscle tendons. Harmonic responses of the ligaments tractions with elastic and hyperelastic behavior are obtained and compared, for different pressure levels, applied on the eardrum.

Geometric and finite element mesh

The geometry of the eardrum and ossicles (malleus, incus and stapes) is constructed using tomography computerized images. These images were obtained from a woman, without ear pathology, and the slices have 0.5 mm of thickness. The finite element meshing of the middle ear is then carried out, including the ligaments (superior, lateral and anterior of malleus, superior and posterior of the incus and annular ligament of the stapes), two muscle tendons (tensor tympani and the stapedius) and the simulation of the cochlear fluid (Figure 1).

The elements of the ossicles (a total of 72150) are four tetrahedral nodes (C3D4 in the ABAQUS program) and the eardrum (3722 elements) is modeled by hexahedral (C3D8). Linear elements (T3D2) model the ligaments and the muscles tendons. The cochlear fluid is modeled with fluid elements (F3D3), supposing isochoric conditions.

Boundaries of the finite element model include tympanic annulus, the connection between the stapes footplate and the cochlea, and the connection of suspensory ligaments and muscle tendons to the temporal bone. The eardrum is fixed in its en-

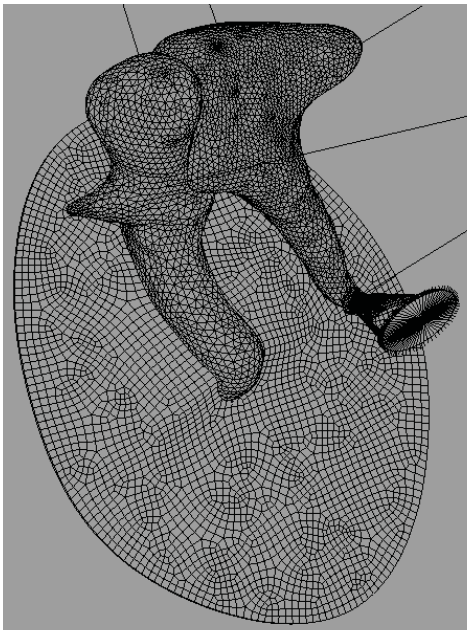

Figure 1: Finite element model of the middle ear.

tire periphery, simulating the tympanic annulus. The boundary that attaches the stapes footplate to the cochlea, in the oval window, simulating the stapes annular ligament, is made by one-dimensional linear elements. The free extremities of these elements are fixed, while the others are connected to the stapes nodes. In terms of the finite element model, suspensory ligaments correspond to the superior and the anterior of malleus and posterior and superior of incus. The four suspensory ligaments are all fixed in these free extremities (superior of malleus and superior of incus simulate the *tegmen tympani*, posterior of incus simulates the *fossa incudis* and anterior of malleus simulate the anterior wall of the tympanic cavity). For lateral ligament of malleus, one extremity attaches to neck of malleus and the other to the tympanic annulus. The tensor tympanic muscle is fixed in the handle of malleus with lateral direction and the stapedius muscle in the posterior crus of stapes.

The connection between ossicles, malleus/incus and incus/stapes, simulating incudomallear and incudostapedial joints, respectively, is done using contact formulation. In this sense, the basic Coulomb friction model available in the ABAQUS program is used, being the friction rate equal to 0.7 (Gentil *et al.* 2007).

The load applied, on the eardrum, is simulated for uniform sound pressure levels of 20, 60, 80, 105 and 120 dB SPL. Thus, to analyze the harmonic response of the umbo and footplate stapes (in terms of displacements), distributed normal loads of 0.2 Pa (80 dB SPL) and 3.56 Pa (105 dB SPL) of sound pressure are applied. To investigate traction on the ligaments, the following loads are considered: 0.0002 Pa (20 dB SPL), 0.02 Pa (60 dB SPL), 0.2 Pa (80 dB SPL) and 20 Pa (120 dB SPL).

Material Properties

In the present work, the eardrum and the ossicles are also assumed to have viscoelastic behavior, with elastic properties summarized in Table 1 (Prendergast *et al.* 1999; Sun *et al.* 2002), assuming an isotropic behavior.

The Poisson's ration is assumed equal to 0.3 for all viscoelastic materials.

Table 1: Some material properties for the eardrum and ossicles.

Material Properties	**Density (Kg/m^3)**	**Young's modulus (N/m^2)**
Eardrum: *Pars tensa* *Pars flaccida*	1.2E+3	2E+7 1E+7
Ossicles Malleus: - head - neck - handle	2.55E+3 4.53E+3 3.70E+3	1.41E+10
Incus: - body - short process - long process	2.36E+3 2.26E+3 5.08E+3	
Stapes	2.20E+3	

Table 2: Material elastic properties for the ligaments and muscle tendons.

Components	**Density (Kg/m^3)**	**Young's modulus (N/m^2)**
Malleus ligaments: Superior Lateral Anterior	1.00E+3	4.9E+4 6.7E+4 2.1E+6
Incus ligaments: Superior Posterior	1.00E+3	4.9E+4 6.5E+5
Stapes ligament: Anular	1.00E+3	1.0E+4
Muscle tendons: Tensor tympanic Stapedius	1.00E+3	2.6E+6 5.2E+5

In several publications on biomechanics, including textbooks, the different body ligaments are presented as having hyperelastic behavior (Peña *et al.* 2006, 2007; Palomar *et al.* 2007; Alastrué *et al.* 2007, among others). Considering the Yeoh model (Yeoh 1990), this work also uses hyperelastic non-linear behavior for the ligaments and muscle tendons, being the present results compared with the elastic model described before.

Assuming the Yeoh constitutive model, the strain-energy function can be written in the following form $\psi = c_1(I_1-3) + c_2(I_1-3)^2 + c_3(I_1-3)^3$, where I_1 is the first right Cauchy-Green tensor invariant (Holzapfel 2000) and c_1, c_2 and c_3 are the material constants which are included in Table 3 for all the ligaments and muscle tendons. Wang *et al.* obtained experimental curves (stress versus stretch) for the eardrum, anterior maleolar, stapedius and tympani tendons (Wang *et al.* 2007). Based on these experimental results, the material constants, for the Yeoh model, were established in the present work (Table 3), assuming that the posterior incudal ligament has the same constants of stapedius tendon. From Table 2, it is possible to verify that the superior maleolar and superior incudal ligaments have the same Young's modulus, as a consequence, the material properties can be assumed equal for both. Additionally, these ligaments have similar values that lateral maleolar and annular ones (Table 3).

Table 3: Material constants for the ligaments and muscle tendons, with hyperelastic behavior.

Ligaments and muscles constants	c_1	c_2	c_3
Malleus:	6.3064E+3	-9.999E+3	2.20445E+6
Superior	7.33869E+4	-3.74378E+2	5.85566E+5
Anterior	6.3064E+3	-9.999E+3	2.20445E+6
Lateral			
Incus:	6.3064E+3	-9.999E+3	2.20445E+6
Superior	5.45889E+4	-4.16989E+4	1.25482E+6
Posterior			
Stapes:	6.3064E+2	-9.999E+3	2.20445E+6
Annular			
Tensor tympanic	2.78105E+4	-1.62848E+4	6.34544E+5
Stapedius	5.45889E+4	-4.16989E+4	1.25482E+6

Using the referred experimental results and the differences of the Young's modulus, new material constants for the superior and lateral of malleus, superior of incus and annular ligaments were also established (Table 3).

To obtain the structural dynamic response of the middle ear system, the solution of the dynamic equilibrium equation is needed. **M**, **C** and **K** represent the mass, the damping and the stiffness matrices, respectively, being **F** the load, for the present work a harmonic function (Cook 1995; Dong *et al.* 1995). Using Rayleigh proportional damping, **C**, is a linear combination of the mass and the stiffness matrices $\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}$ where α and β are the damping parameters. The assumed damping coefficients are $\alpha = 0$ s^{-1} and $\beta = 0.0001$ s (Prendergast *et al.* 1999; Sun *et al.* 2002).

Results

Structural response to harmonic vibrations

Considering a sound pressure level of 80 dB SPL and 105 dB SPL, applied on the eardrum and the two constitutive models (elastic and hyperelastic) for the ligaments and muscle tendons, umbo and stapes footplate displacements are obtained from a frequency range between 100 Hz to 10 kHz. Comparing the two models, one can conclude that for the umbo displacement (Figure 2) there is only a little difference for the low frequencies. For the stapes footplate displacement (Figure 3), a lower curve in the simulation of elastic model is obtained for all frequencies.

To confirm the validity of the present model, the obtained results are compared with other works published in the literature (Nishihara *et al.* 1996; Huber *et al.* 1997; Prendergast *et al.* 1999; Gan *et al.* 2004; Lee *et al.* 2006). Lee *et al.* compare their results with experimental data, obtained from human temporal bones (Nishihara *et al.* 1996 and Huber *et al.* 1997).

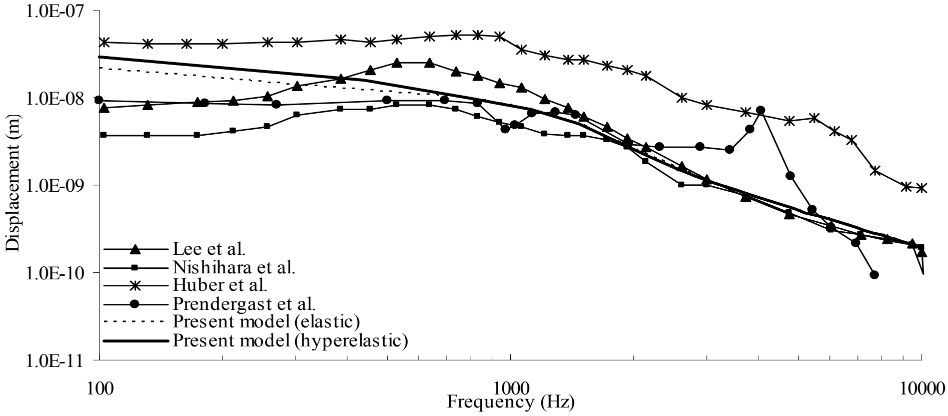

Figure 2: Umbo displacements for a sound pressure level of 80 dB SPL.

For the motion of the umbo (Figure 2), the results obtained are closed to those obtained by Prendergast *et al.*, Lee *et al.* and Nishiahara *et al.* and smaller than the experimental results from Huber *et al.*.

In Figure 3, the displacements of the stapes footplate are also compared with other works (Prendergast *et al.* 1999; Gan *et al.* 2004 and Lee *et al.* 2006). For some middle frequencies, the obtained values are smaller than those presented by

Lee *et al.*, but for other frequencies, there are any significant differences. Considering now the results established by Gan *et al.*, the most significant differences occur at high frequencies.

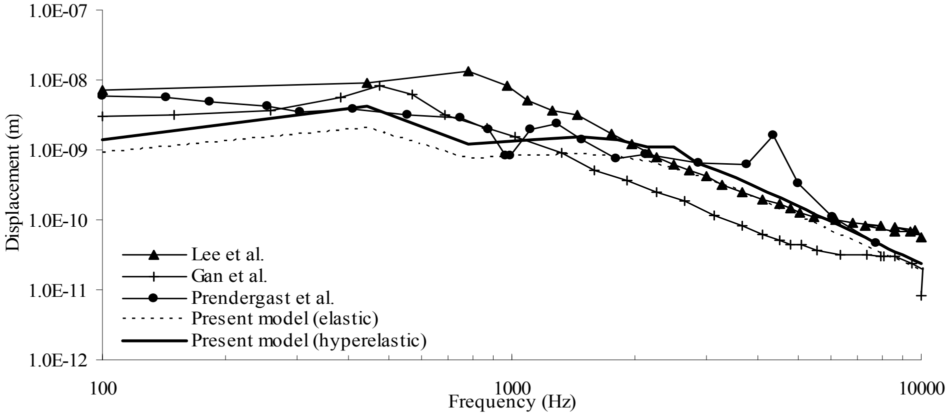

Figure 3: Stapes footplate displacements for a sound pressure level of 80 dB SPL.

In conclusion, for the movement of the stapes footplate, the presented results are closed to the ones obtained by Prendergast et al., with a little difference for low frequencies (< 300 Hz).

Considering a sound pressure level of 105 dB SPL, applied on the eardrum, the umbo and stapes footplate displacements (Figure 4 and Figure 5 respectively) are obtained and compared with the work of Kurokawa *et al.* (Kurokawa *et al.* 1995).

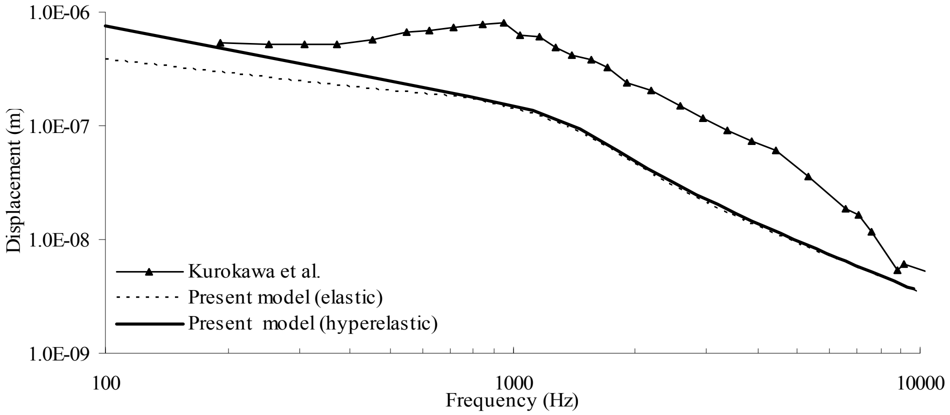

Figure 4: Umbo displacements, for a sound pressure level of 105 dB SPL.

In this case, the results are lower than the values obtained by Kurokawa *et al.*, with significant differences for frequencies around 1 kHz.

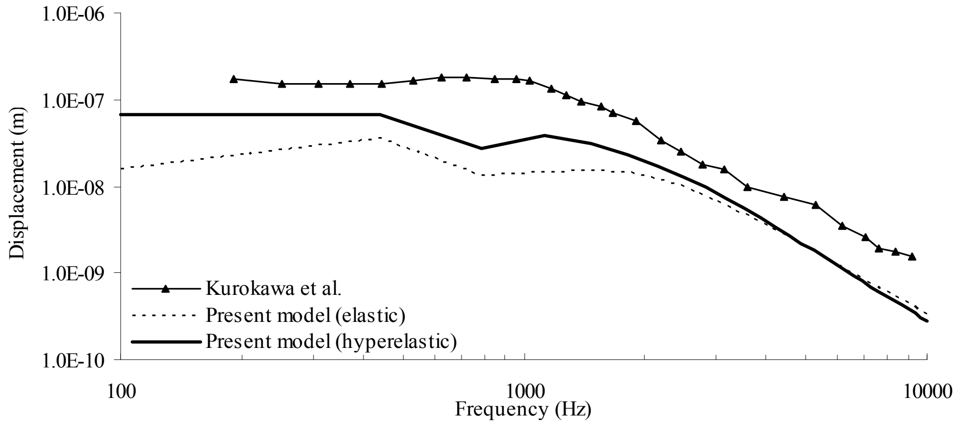

Figure 5: Stapes footplate displacements, for a sound pressure level of 105 dB SPL.

Traction in the suspensory ligaments

The traction, measured as normal stresses, applied in the ligaments (superior and anterior of malleus and superior and posterior of incus) are shown in Figure 6 and Figure 7, using elastic and hyperelastic constitutive models respectively. Four different sound pressures were applied on the eardrum, 20, 60, 80 and 120 dB SPL.

For the model with elastic behavior, the ligament with highest traction is the anterior of malleus, presenting the two superior ligaments, small values.

In case of hyperelastic model, one can conclude that the ligament that reaches the biggest traction peak is the posterior of incus (for example, considering 120 dB SPL, the biggest value of 3335.6 Pa is obtained for a frequency of 294.7 Hz and 0.03336 Pa for 20 dB SPL). The other ligaments also have a peak value near this frequency but with smaller values. The superior ligament of malleus and superior ligament of incus present smaller traction values.

Discussion

In this work, a biomechanical dynamic study of the middle ear was conducted, considering its harmonic response and the traction of the suspensory ligaments. Considering the suspensory ligaments and muscle tendons, two constitutive models were considered with elastic and hyperelastic behavior.

The structural response to harmonic vibrations was analyzed. Harmonic responses of the umbo and stapes footplate displacements were obtained from 100 Hz to 10 kHz, for a sound pressure level of 80 and 105 dB SPL, applied on the eardrum. The obtained results were compared with other published works. The present simulations show some differences between the two constitutive models. The displacements obtained for the stapes footplate considering the hyperelastic model are greater than those obtained with the elastic law for the frequency range considered. However, for the umbo displacements the smaller values occur for the

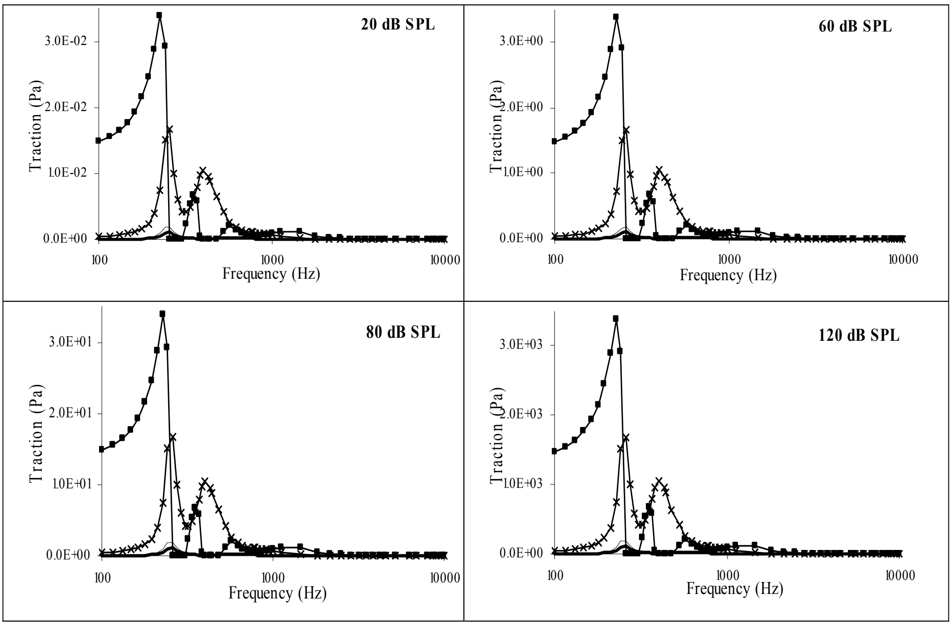

Figure 6: Traction (Pa) of malleus and incus suspensory ligaments, with elastic behavior, for different sound pressure levels with a frequency range between 100 Hz and 10 kHz.

elastic behavior and also for lower frequencies. The results obtained with Yeoh model are closer to the results available in literature.

The second part of the current study was the analysis of the traction on the ligaments and muscle tendons for the human audible frequency range. The simulations performed have shown significant differences between the two constitutive models. When the elastic model is considered, the biggest traction of values is obtained in the malleus anterior. However, if the hyperelastic model is assumed, the biggest peak of traction is obtained in the posterior of incus. In both, two superior ligaments have smaller traction values.

The conclusion of this work allows to emphasize the importance of the use of hyperelastic models instead of a linear elastic behavior for the ligaments and tendons.

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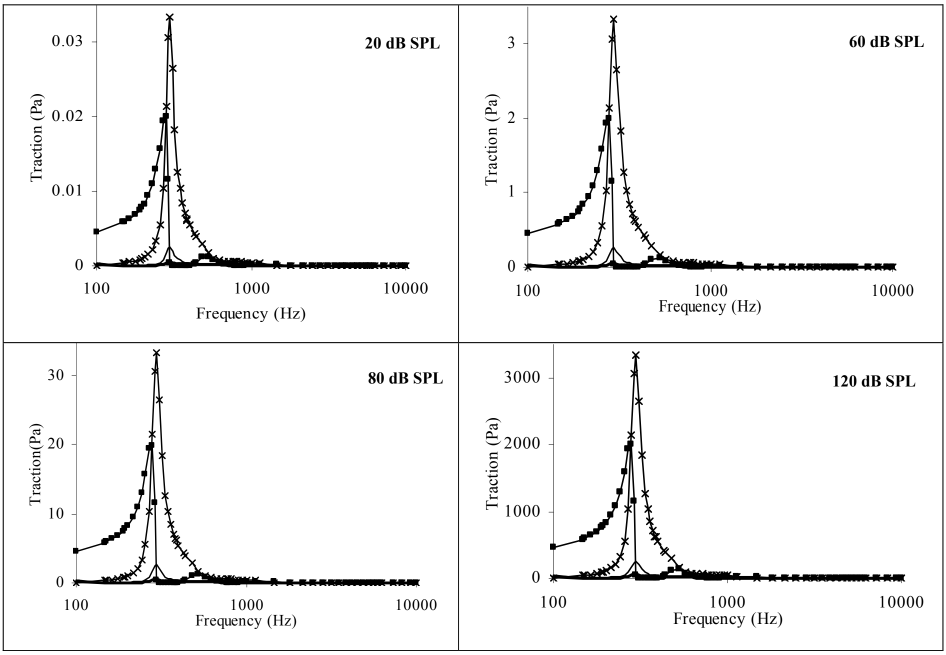

Figure 7: Traction (Pa) of malleus and incus suspensory ligaments, with hyperelastic behavior, for different sound pressure levels with a frequency range between 100 Hz and 10 kHz.

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