Influence of Pipette Geometry on the Displacement Profile of Isotropic Materials used for Vocal Fold Modeling

Sandra Weiß[1], Scott L. Thomson[2], Alexander Sutor[1], Stefan J. Rupitsch[1] and Reinhard Lerch[1]
[1]*Chair of Sensor Technology, Friedrich-Alexander-University, Erlangen, Germany*
[2]*Department of Mechanical Engineering, Brigham Young University, Provo, Utah, U.S.A.*

Keywords: Pipette Aspiration, Vocal Folds, Inverse Method, Rectangular Cross-sectional Pipette.

Abstract: Due to limited access to human vocal folds, synthetic vocal folds are used to study periodic phonation. With respect to a realistic replica, the properties of the synthetic material should be to those of as real tissue. Silicone rubber is a commonly used material for vocal fold models. A suitable method to analyze the material parameters of both artificial and real vocal folds is the pipette aspiration technique. In the present study, the displacement profiles of an isotropic silicone specimen were measured with three different pipette geometries. The experimental results were compared to finite element simulations of the setup based on frequency dependent material parameters extracted from a previous study. The results demonstrate the potential of the pipette aspiration technique for material characterization and validate the determination of material parameters by means of an Inverse Method. Furthermore, a possible parameter for the classification of anisotropic materials is proposed and the suitability of the different pipette geometries for material characterization is discussed.

1 INTRODUCTION

Flow-induced vibrations of the vocal folds (phonation) initiate the sound for most human voicing. In order to better understand the periodic parts of phonation, the vibratory characteristics of the vocal folds have to be analyzed. The vocal folds are comprised of multiple layers of tissues with different properties. Their morphology can be divided into three main regions (Hirano, 1981): the body, the ligament, and the cover. The cover is the most superficial layer and is mainly composed of an extracellular matrix and loose fibers (Gray, 2000). In contrast, the ligament (middle layer) contains a high density of elastin and spiraling collagen fiber bundles oriented in anterior-posterior direction, leading to a transversely isotropic material behavior (Hammond et al., 1997). The deepest and thickest layer (body) consists of muscle fibers (Finck and Dejeune, 2010).

Due to limited in vivo access to human vocal folds and rapid degradation of excised larynges, artificial vocal folds are being increasingly used to study the mechanics of flow-induced vibration. It is important that these replicas possess similar material properties as real tissue. Because silicone rubber offers similar stiffness characteristics, vocal fold models have been fabricated using this material. Different approaches, including single-layer models (Becker et al., 2009) and multi-layer models with variations in stiffness between the layers (Pickup and Thomson, 2009) have been presented.

In order to compare the properties of synthetic model materials with those of real vocal fold tissue, there is a need for measurement methods capable of determining the mechanical material parameters of these types of synthetic materials and tissues over a range of physiologically-realistic frequencies. In the following, some candidate techniques are briefly summarized and assessed, noting the ultimate goal of improvement of the clinical care of the human voice.

The measurement of the static elasticity modulus of synthetic and real vocal folds is performed by tensile tests (Alipour-Haghighi and Titze, 1991). However, the properties of real vocal fold tissue are frequency-dependent (Chan and Titze, 1999). Consequently, measurement techniques to analyze the dynamic behavior are needed.

The frequency-dependent material parameters of single layer silicone samples can be measured with a so-called vibration transmission analyzer (Rupitsch et al., 2011). In this approach, an isotropic silicone specimen with known geometry is mounted on an electromechanical shaker. A harmonic oscillation is induced at the bottom surface, the velocity of which

Weiß S., L. Thomson S., Sutor A., J. Rupitsch S. and Lerch R..
Influence of Pipette Geometry on the Displacement Profile of Isotropic Materials used for Vocal Fold Modeling.
DOI: 10.5220/0004191801080113
In *Proceedings of the International Conference on Biomedical Electronics and Devices* (BIODEVICES-2013), pages 108-113
ISBN: 978-989-8565-34-1

is measured with an acceleration sensor. The velocity at the centerpoint of the specimen's top surface is measured with a laser vibrometer. The magnitude of the transfer function between the two velocities is calculated over a frequency range of 10 -400 Hz. The experimental results are compared to corresponding finite element simulation results and the dynamic material parameters are estimated using an Inverse Method (Rupitsch and Lerch, 2009). Although, this method provides dynamic information, only specimens with known geometry can be investigated, which typically precludes investigations of real tissue.

One possible method for the material characterization of real and artificial vocal fold materials is the pipette aspiration technique. A first approach to estimate the static elasticity modulus of homogeneous, isotropic materials was published in (Aoki et al., 1997). It was shown that by placing a pipette on a soft material and applying static suction, the Young's modulus of that region can be calculated by measuring the maximum aspiration displacement as a function of aspiration pressure. Further studies have applied this technique to real tissue, e.g., (Matsumoto et al., 2002; Henriksen and Ipsen, 2004). By replacing the static pressure with a fluctuating pressure, frequency-dependent analysis has been enabled (Zörner et al., 2010). Moreover, in (Ohashi et al., 2005) the technique was applied to the measurement of anisotropic properties of blood vessels under biaxial stretch. It was shown that by using a rectangular cross-sectioned pipette, the static elasticity modulus along the length could be neglected. As a result, by choosing an appropriate pipette geometry, anisotropic regions can be characterized. Moreover, the suitability of the pipette aspiration technique for the characterization of inhomogeneous transversely isotropic silicone samples was recently demonstrated by (Weiss et al., 2013). All these studies show the potential of the pipette aspiration technique for determining the material properties of synthetic materials and real tissue. The technique is spatially-resolved and it could potentially be used in *in vivo* investigations. Therefore, this method could help in the development of a more realistic vocal fold model by comparing measurements of synthetic materials to those of real tissue.

In this paper, we focus on the feasibility of the proposed measurement method by measuring the displacement profiles of isotropic silicone samples with three different pipette geometries at a frequency of 120 Hz. The experimental results are compared with finite element predictions using a model with material properties taken from (Rupitsch et al., 2011), validating the experimental procedure as well as the determination of the material parameters.

2 MATERIALS AND METHODS

2.1 Silicone Specimens

The two-part addition-cure silicone rubber *Ecoflex 0030* (Smooth-On, Inc.) was used to fabricate cuboid silicone specimens measuring 50 mm × 50 mm × 10 mm. This material consists of equal parts of the two subcomponents. By adding a variable amount of silicone thinner, the specimen's stiffness is reduced. In this study, mixtures with three parts of thinner (namely 1:1:3) were used. The static elasticity modulus of samples made using this mixing ratio has been previously measured using tensile tests to 7.02 kPa ± 0.29 kPa (Ilg et al., 2012).

2.2 Pipette Aspiration Setup

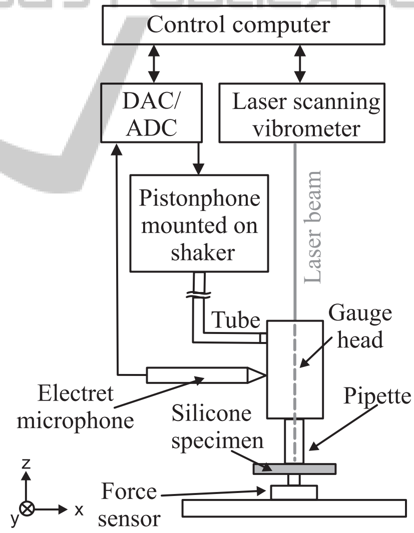

Figure 1: Pipette aspiration setup.

The measurement setup is shown in Figure 1. The specimen was positioned on a plate. The pipette was pressed against the surface of the specimen and the contact force, measured by the force sensor, was maintained at 0.2 N. The gauge head was connected to a pistonphone that was mounted on a shaker to generate a fluctuating pressure within the gauge head. The excitation frequency (here 120 Hz) and amplitude of the mechanical oscillation were controlled via LabVIEW©. The actual pressure amplitude was acquired by the microphone and kept constant at 20 Pa. Using a laser scanning vibrometer (*PSV 300*, Polytec), the out-of-plane velocity at several points on a measurement grid coinciding with the aspiration area of the pipette was measured.

2.3 Pipette Configurations

For the experiments, three pipettes of different end geometries were applied, and the resulting displacement profiles were analyzed. The top views of the pipette cross sections are schematically shown in Figure 2. One pipette was circular with an inner diameter of 3 mm and an outer diameter of 12 mm (Figure 2a)). Another pipette had a rectangular cross section (Figure 2b)) with outer dimensions of the pipette area of 12 mm × 12 mm. The aspiration area measured 4 mm × 1 mm. Finally, a cross-shaped pipette (Figure 2c)) with similar pipette size was used. The long axis measured 4 mm and the short axis measured 1.5 mm.

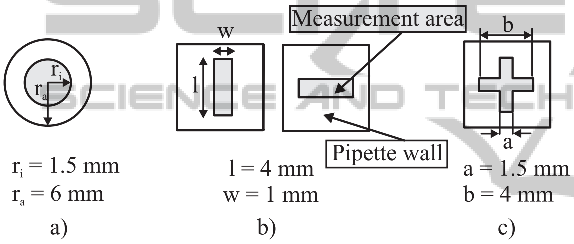

Figure 2: Pipette configurations investigated in this study: a) circular, b) rectangular and c) cross-shaped measurement areas.

2.4 Finite Element Simulations

Finite element simulations were performed to (i) explore the dynamic material properties proposed in (Rupitsch et al., 2011), (ii) to validate the simulations by comparison with experiments, and (iii) investigate the influence of different pipette configurations on the measured displacement profiles.

2.4.1 Simulation Model

Figure 3 shows the three-dimensional finite element model geometry of the measurement system with a cross-shaped pipette. The cuboid specimen with an edge length of 50 mm and a height of 10 mm was modeled using the ANSYS© preprocessor and solved using the finite element software CFS++ (Coupled Field Simulation) (Kaltenbacher, 2007). The pipettes were modeled as the ends of either an annulus or a hollow block. The total number of nodes and elements for the different models are summarized in Table 1.

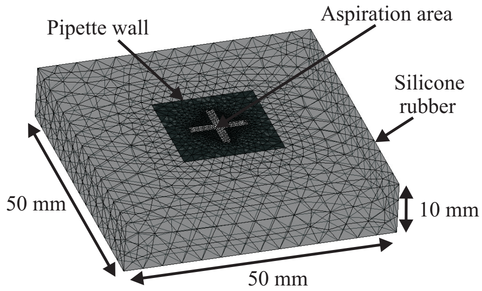

Figure 3: Finite element model geometry with a cross-shaped pipette.

Regarding boundary conditions, the bottom nodes of the cuboid were fixed to simulate the silicone specimen placement on a plate in the experiment. Since the experiments were performed with a contact force of 0.2 N, a static analysis was executed in the first step of the simulations, applying an appropriate pressure on the pipette wall. Harmonic analysis with fixed boundary conditions at the pipette wall was then performed. The specimen surface displacement within the aspiration area was calculated for a 120 Hz fluctuating pressure with an amplitude of 20 Pa.

2.4.2 Input Material Parameters

The dynamic material parameters were extracted from (Rupitsch et al., 2011). In that study, the frequency-dependent Young's modulus, damping factor, and Poisson's ratio values of a cylindrically-shaped silicone sample with the same mixing ratio were determined using an inverse scheme (Rupitsch and Lerch, 2009) based on a Gauss-Newton algorithm. The results served as input parameters for the performed simulations and are therefore briefly summarized. The Poisson's ratio was calculated to remain constant over frequency with a value of 0.499. The damping factor was estimated to be 0.13. The following frequency-dependent real and imaginary parts of the Young's modulus of the 1:1:3 silicone mixture were obtained

$$\frac{E_{\mathrm{R}}(f)}{\mathrm{Pa}} = 7.02\cdot 10^3 + 9.82\cdot\frac{f}{\mathrm{Hz}} + \dots$$

$$\dots + 8.59\cdot 10^2\cdot\log_{10}\left(\frac{f}{\mathrm{Hz}}+1\right)$$

$$\frac{E_{\mathrm{I}}(f)}{\mathrm{Pa}} = 3.85\cdot 10^3 + 11.5\cdot\frac{f}{\mathrm{Hz}} + \dots$$

$$\dots - 1.13\cdot 10^3\cdot\log_{10}\left(\frac{f}{\mathrm{Hz}}+1\right).$$

3 RESULTS

The displacement profiles of an isotropic 1:1:3 silicone specimen were measured using the pipettes shown in Figure 2. A circular measurement grid was used for the circular pipette and a quadratic grid was used for the rectangular and cross-shaped pipettes, respectively. To ensure acquisition throughout the aspiration area, the measurement grid extended beyond the aspiration area by about 0.5 mm along each edge.

The top view and the profile cross sections in orthogonal x- and y-directions are shown in the second and third columns of Figure 4, respectively. The dashed lines show the profiles in the y-direction, the solid lines in the x-direction. Due to reflections at the pipette wall, the edges of the area enclosed by the pipette are diffuse and the displacements at the grid edges are overestimated and therefore not zero.

Table 1: Numbers of nodes and elements for the different finite element models. The numbers in parentheses list the nodes and elements within the aspiration area.

Pipette	Nodes	Elements
circular	68605 (3364)	46583 (1200)
rectangular	73794 (2185)	54149 (1152)
cross-shaped	66500 (1617)	50132 (858)

The measurement results are compared to those of the finite element simulations, described in Section 2.4. The fourth and fifth columns of Figure 4 show the computational results. The comparison of the profile cross sections shows very good quantitative agreement between the experimental and the computational displacements. Moreover, the profile shapes of both simulations and experiments are similar.

The computational results also demonstrate that the determination of the dynamic material parameters with the vibration transmission analyzer (Rupitsch et al., 2011) by means of an inverse scheme is suitable for synthetic materials used for vocal fold modeling. This is evidenced by the calculated material parameters serving as input for the finite element simulations in this study. The presented results provide evidence that both platforms (numerical and experimental approaches) are valid tools for exploring various extensions and applications of the pipette aspiration technique pertaining to material property characterization.

With respect to the profile cross sections, the circular pipette showed a parabolic form and axisymmetric profiles. The profiles of the cross-shaped pipette matched as well. Both measurements with the rectangular pipette (see Figure 2b)) yielded similar cross sections along long and short axes. As we investigated an isotropic specimen, this was expected. However, parts of the human vocal folds exhibit a transversely isotropic behavior. In a previous study (Ohashi et al., 2005), a rectangular pipette was used for the measurement of anisotropic material properties. It was found that the elasticity along the length can be neglected. Consequently, the displacement profiles of the circular and cross-shaped pipette were supposed to deviate from axisymmetry in case of a transversely isotropic specimen. For the rectangular pipette, the displacements for the two configurations in Figure 2b) would be different. For that reason, we propose a new measure, the numerical parameter A^*, to quantify the degree to which the investigated material exhibits anisotropic behavior. The area of the x-profile, A_x, can be calculated by integrating the displacements, $d(x,0)$ in the x-z-plane for $y = 0$ over the x-direction span, l:

$$A_x = \int_{-\frac{l}{2}}^{+\frac{l}{2}} d(x,0)\mathrm{d}x. \tag{1}$$

For the orthogonal y-direction, the corresponding area is calculated by

$$A_y = \int_{-\frac{l}{2}}^{+\frac{l}{2}} d(0,y)\mathrm{d}y. \tag{2}$$

The ratio of these two areas, $A^* = A_y/A_x$, quantifies the deviation of the profile from axisymmetry.

Table 2: A^*-values for the measured and simulated profiles shown in Figure 4.

Pipette	A^*	
	Experiment	Simulation
circular	1.01	1.00
rectangular (length l)	0.99	1.00
rectangular (width w)	0.99	1.00
cross-shaped	0.99	1.00

The displacement profiles were analyzed with respect to A^*. Since the profile of the rectangular pipette was not axisymmetric, the two configurations shown in Figure 2b) were compared. The displacements over the length l of both configurations were integrated and divided by each other to calculate the A^*-value for the profiles parallel to the long axis of the rectangular area. The A^*-value for the profiles parallel to the width w were similarily obtained. The A^*-results are summarized in Table 2. For all specifications, the A^*-value is equal or nearly equal to 1, which is consistent with expectations of an isotropic material. According

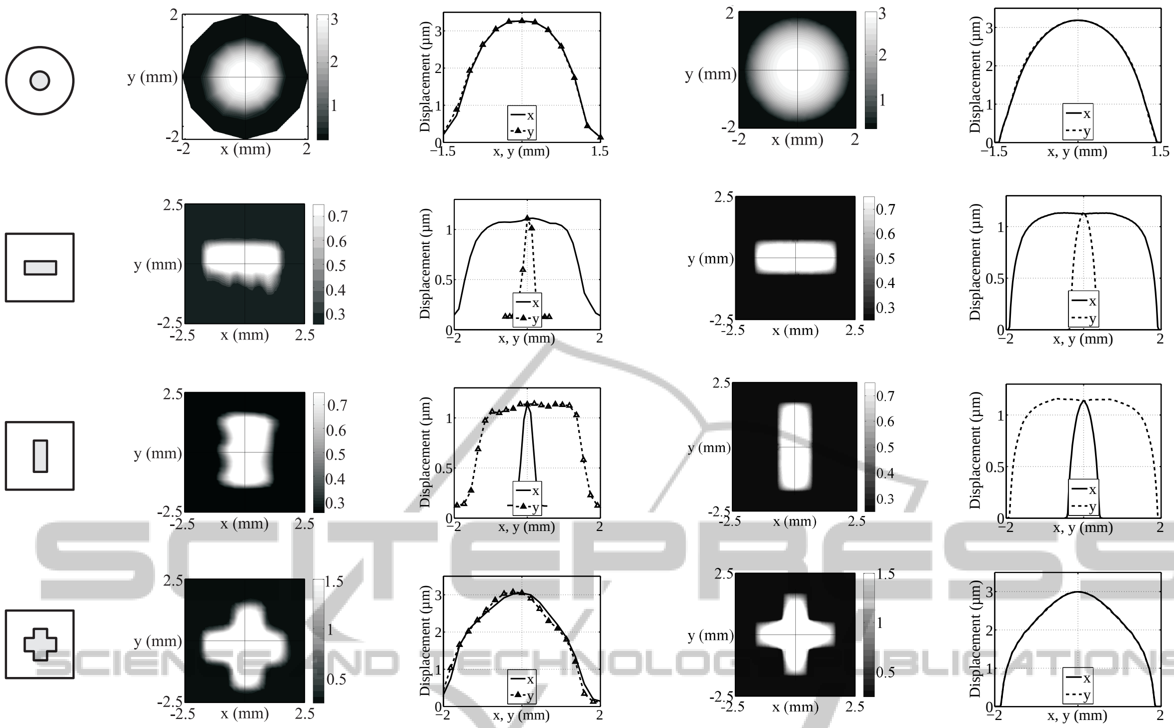

Figure 4: Experimental and computational results for isotropic materials: The pipette geometry is schematically shown in the left column, the top view and profile cross sections of the measured displacement profiles are plotted in the second and third column, whereas the corresponding simulations are plotted in the last two columns.

to (Ohashi et al., 2005), anisotropic materials were sensitive to the stiffness parallel to the width of the rectangular pipette. As a result, for anisotropic materials, we expect that the A^*-value should differ from 1 and could therefore serve as a quantitative measure of the degree of anisotropy.

4 DISCUSSION

Three different pipette geometries were utilized and the displacement profiles of an isotropic silicone sample with properties similar to real vocal fold tissue were measured. Moreover, the profile cross sections in orthogonal directions were analyzed and the experimental results were compared to finite element simulations of the setup. The results demonstrate that the pipette aspiration technique is suitable for investigating soft materials used for vocal fold modeling. Furthermore, the material parameter determination by means of an Inverse Method (Rupitsch and Lerch, 2009) was validated as results from a previous study (Rupitsch et al., 2011) served as input parameters for the simulation.

To characterize whether the investigated material is isotropic or exhibits anisotropic properties, the numerical parameter A^* describing the deviation from profile axisymmetry was introduced. The value tends to 1 for isotropic materials whereas anisotropic materials lead to a value smaller or greater than 1, as has been previously demonstrated (Weiss et al., 2013).

Because the applied pipette configurations showed different profile cross sections, the present pipette aspiration setup could be an appropriate way to acquire information about inhomogeneous and anisotropic regions of a specimen. The setup can also be applied to measurements of real tissue. Importantly, comparing such data from both synthetic materials and real tissue will likely yield improvements in synthetic material development, leading to improved vocal fold models.

Two challenges are noted. First, aspiration areas with a diameter smaller than 1 mm in the current setup are not possible due to insufficient focusing of the laser beam. A second issue is the sensitivity of the results to the specimen's roughness, which is yet to be explored.

Future studies will deal with a computational study on the displacement profiles of transversely isotropic materials to determine an optimal pipette configuration for investigations on such materials.

5 CONCLUSIONS

The material characterization of silicone rubber used for vocal fold modeling by means of pipette aspiration was proposed. Different aspiration areas were compared with respect to the resulting displacement profiles. Finite element simulations based on frequency-dependent material parameters were performed which showed similar results revealing the potential of both, the pipette aspiration technique for the characterization of soft materials and the determination of dynamic material parameters using an Inverse Method (Rupitsch and Lerch, 2009). By calculating the ratio of the areas of the displacement profiles in orthogonal directions, a quantitative parameter for an isotropic material behavior was presented. Because this study validates both, the measurement procedure and the numerical model, it provides a basis for future studies dealing with similar characterizations of synthetic materials used for vocal fold modeling.

ACKNOWLEDGEMENTS

The presented work was supported by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Grant No. FOR 894/2, and by Grant Number R01DC009616 from the U.S. National Institute on Deafness and Other Communication Disorders (NIDCD). Dr. Thomson gratefully acknowledges support as a visiting professor from the University of Erlangen Graduate School in Advanced Optical Technologies (SAOT).

REFERENCES

Alipour-Haghighi, F. and Titze, I. R. (1991). Elastic models of vocal fold tissues. *Journal of the Acoustical Society of America*, 90:1326–1331.

Aoki, T., Ohashi, T., Matsumoto, T., and Sato, M. (1997). The pipette aspiration applied to the local stiffness measurement of soft tissues. *Annals of Biomedical Engineering*, 25:581–587.

Becker, S., Kniesburges, S., and Müller, S. (2009). Flow-structure-acoustic interaction in a human voice model. *Journal of the Acoustical Society of America*, 125:1351–1361.

Chan, R. W. and Titze, I. R. (1999). Viscoelastic shear properties of human vocal fold mucosa: measurement methodology and empirical results. *Journal of the Acoustical Society of America*, 106:2008–2021.

Finck, C. and Dejeune, L. (2010). *Handbook of Mammalian Vocalization*, chapter Structure and oscillatory function of the vocal folds, pages 427–438. Elsevier.

Gray, S. D. (2000). Cellular physiology of the vocal folds. *Voice disorders and Phonosurgery I*, 33:679–697.

Hammond, T. H., Zhou, R., Hammond, E. H., Pawlak, A., and Gray, S. D. (1997). The intermediate layer: A morphologic study of the elastin and hyaluronic acid constituents of normal human vocal folds. *Journal of Voice*, 11(1):59–66.

Henriksen, J. R. and Ipsen, J. H. (2004). Measurement of membrane elasticity by micro-pipette aspiration. *The European Physical Journal E*, 14:149–167.

Hirano, M. (1981). *Clinical examination of Voice*. Springer.

Ilg, J., Rupitsch, S. J., Sutor, A., and Lerch, R. (2012). Determination of dynamic material properties of silicone rubber using one-point measurements and finite element simulations. *IEEE Transactions on Instrumentation and Measurement*, 61:3031–3038.

Kaltenbacher, M. (2007). *Numerical Simulations of Mechatronic Sensors and Actuators*. Springer.

Matsumoto, T., Abe, H., Ohashi, T., Kato, Y., and Sato, M. (2002). Local elastic modulus of atherosclerotic lesions of rabbit thoracic aortas measured by pipette aspiration method. *Physiological Measurement*, 23:635–648.

Ohashi, T., Abe, H., Matsumoto, T., and Sato, M. (2005). Pipette aspiration technique for the measurement of nonlinear and anisotropic mechanical properties of blood vessels under biaxial stretch. *Journal of Biomechanics*, 38:2248–2256.

Pickup, B. A. and Thomson, S. L. (2009). Influence of asymmetric stiffness on the structural and aerodynamic response of synthetic vocal fold models. *Journal of Biomechanics*, 42:2219–2225.

Rupitsch, S. J., Ilg, J., Sutor, A., Lerch, R., and Döllinger, M. (2011). Simulation based estimation of dynamic mechanical properties for viscoelastic materials used for vocal fold models. *Journal of Sound and Vibration*, 330:4447–4459.

Rupitsch, S. J. and Lerch, R. (2009). Inverse method to estimate material parameters for piezoceramic disc actuators. *Applied Physics A: Material Science & Proceedings*, 97:735–740.

Weiss, S., Thomson, S. L., Lerch, R., Döllinger, M., and Sutor, A. (2013). Pipette aspiration applied to the characterization of nonhomogeneous, transversely isotropic materials used for vocal fold modeling. *Journal of the Mechanical Behavior of Biomedical Materials*, doi: 10.1016/j.jmbbm.2012.08.005.

Zörner, S., Kaltenbacher, M., Lerch, R., Sutor, A., and Döllinger, M. (2010). Measurement of the elasticity modulus of soft tissues. *Journal of Biomechanics*, 43:1540–1545.