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# A MICRO-MECHANICAL MODEL OF THE VOCAL-FOLD UPPER LAYERS

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## Introduction

The vocal folds are soft multi-layered laryngeal tissues, owning remarkable vibro-mechanical performances. Composed of collagen and elastin microfibrils' networks, the upper layers play a major role in the vocal-fold vibrations. However, the impact of these tissues' histological features on their mechanical behavior is still poorly known. This is mainly ascribed to their challenging experimental characterization: vocal folds together with their fibrous architectures are not easily observable *in vivo*; *ex vivo* mechanical tests are rare and complex to interpret [1]. Consequently, most of the vocal-fold mechanical models developed so far rely on phenomenological macroscopic approaches, roughly assuming a homogeneous vocal tissue with linear-elastic properties. Since 2010, a few authors have started to investigate and model the vocal-tissue collagenous fibrous microstructure, opening a new insight into voice biomechanics [2]. Theoretical formulations at the fiber scale still need to be developed. Thereby, this study aims at: (i) proposing an idealized but relevant model of the fibrous architecture of the vocal-fold upper layers; (ii) building a mechanical model able to predict the layers' multiscale properties from the above idealized architectures; (iii) assessing its relevance by comparison with a reference tensile database.

## Methods

**Idealization of the layer fibrous architectures** – The vocal-fold upper layers can be seen as a 3D composite structure made of a soft isotropic hyperelastic matrix, reinforced by a periodic network of bundles of wavy collagen fibrils displaying preferred orientations. This fibrous architecture is idealized by the Representative Elementary Cell (REC) shown in Fig.1(a). Most of the REC parameters can be extracted from existing histological data [1,2,4]: fibril diameter ( $d_0 \approx 0.1 \mu\text{m}$ ) and length  $l^f$ , initial tortuosity ( $\xi_0 \approx 0.84; 0.92$ ) and lattice length ( $l_0 \approx \xi_0 l^f \approx 20; 30 \mu\text{m}$ ), collagen fibrils content ( $\phi \approx 0.15$ ), initial orientation of fibril bundles ( $\theta_0 \approx 67.5^\circ$ ) with respect to vocal-fold main direction.

**Multiscale model** – To determine the macroscale mechanical response of the as-idealized upper layers under simple uniaxial tensile loading, a non-linear and anisotropic multiscale model is proposed. This theoretical model is written using the homogenization method for periodic discrete structures, as already applied to the context of vascular biomechanics [3]. For that purpose, attention is paid to build a relevant micromechanical model describing the unfolding and

the tensile deformation of wavy collagen fibrils, accounting for their elastic properties [4, 5].

## Results and discussion

The prediction of collagen fibrils' tensile behavior ( $\sigma_f, \lambda_f$ ) is plotted in Fig.1(a) for two typical fibril tortuosities:  $\xi_0 \approx 0.84; 0.92$  [2]. Unfolding the fibrils conducts to typical J-shaped stress-elongation curves depending on  $\xi_0$ . Once the fibril unfolded, curves show a linear evolution with a tangent modulus of 1 GPa [4].

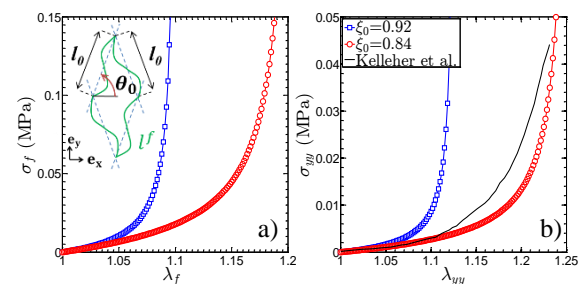


Figure 1: Stress-elongation curves for tensile tests along  $e_y$ : (a) model predictions for the fibril (b) model predictions and experimental data for the tissue.

The macroscale predictions of the multiscale model are given by the stress-elongation curves plotted in Fig.1(b) for the same  $\xi_0$  values. The mechanical behavior of the vocal ligament under tension is also illustrated in Fig.1(b), as an experimental reference recently reported using DIC measurements [1]. As observed at the microscale in Fig.1(a), both macroscale curves exhibit a J-shaped non-linear mechanical behavior, characteristic of collagenous soft tissues. Fig.1(b) also demonstrates a fairly good quantitative agreement with the reference mechanical data, keeping in mind that all model parameters derived from histological evidences. Further used to simulate *in vivo* loadings, this model will help to understand the role of the fibrous networks in vocal-fold vibratory properties. It will also provide proper guidelines to design new composites mimicking vocal-fold biomechanics.

## References

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