VOCAL FOLD VISCO-HYPERELASTIC PROPERTIES: CHARACTERIZATION AND MULTISCALE MODELING UPON FINITE STRAINS

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Objectives: Analytical models currently simulating vocal folds mechanical behavior at the fiber scale are very promising to better understand their remarkable macroscale performances. In continuity with these developments, this study aims at proposing a 3D multiscale biomechanical model of the vocal tissue able to properly predict its time-dependent properties upon finite strains.

Introduction: Since the 2010s, the investigation and modeling of human vocal-fold fibrous microstructure has opened a new insight into voice biomechanics [1,2,3]. So far, most of the multiscale formulations have focused on the *lamina propria* anisotropic and hyperelastic properties, predicting the unfolding of crimped collagen fibers and, consequently, the tissue's J-shaped response under large-strains uniaxial tensile loading. A few authors have proposed a 1D viscoelastic model of *lamina propria* in tension, to better investigate the regulation of key phonatory parameters such as the acoustic fundamental frequency [4]. *In vivo*, however, vocal folds are subjected to numerous complex and coupled 3D mechanical solicitations (tension, compression and shear), experienced upon finite strains and at various strain rates. Therefore, this work presents: (i) a set of data completing the available characterization of vocal-fold viscoelasticity under multiple mechanical loadings [4,5]; (ii) a 3D micro-mechanical model of the tissue layers, able to predict their visco-hyperelastic and anisotropic properties.

Methods: Histological descriptors of the fibrous networks within *lamina propria* and *vocalis* layers were firstly collected from 2D/3D human vocal folds images [3]. Available measurements of their time-dependent response [4,5] were then completed by mechanical tests performed on excised samples subjected to finite strain loadings (cyclic traction, compression, shear, relaxation). These tests were conducted by means of a dedicated micro-press coupled with an optical tracking of the deformed samples. A 3D homogenized micro-mechanical model was also developed, to predict the macroscale anisotropic and hyperelastic properties of the tissues [6]. The formulation was furtherly enriched by adding a Maxwell viscoelastic stress contribution to the hyperelastic stress of each collagen fiber. The model is therefore able to simulate a large variety of loading conditions at various rates.

Results: The optimized microscale parameters of the model are successfully compared to 2D/3D histo-mechanical data and critically commented. The resulting model predictions can reproduce a wide range of loading paths, from small to finite strains. For each loading, predicted stress-strain responses are discussed with regard to the evolution of the microstructure within collagen and muscular fibrous networks. Particular attention is paid to the coupling between the fibers rotation and their own deformability. The influence of the strain rate and strain amplitude on the *lamina propria* and *vocalis* mechanical behaviors is also highlighted.

Conclusions: This study points out the finite strain and time-dependent mechanical response of the vocal-fold sublayers under various physiological loadings, which are barely studied experimentally or theoretically so far. These advances are expected to provide a better understanding of the link between the micromechanics of vibrating tissues and their macroscale performances.

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