STUDY OF BIOMECHANICAL PROPERTIES OF VITREOUS HUMOR BY A FINITE ELEMENT MODEL

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Abstract: A finite element (FE) model was proposed to simulate the viscoelastic interaction between vitreous humor and ophthalmic micro surgical instruments. Wireless intraocular microrobots have been proposed for performing prospective microsurgical operations. The FE model was calibrated using experimental data on an ex vivo human vitreous humor. The proposed FE model was then used to study the shape-dependent interaction between the microrobots and the vitreous. The knowledge on the geometry of microrobots is essential in optimizing their design for ophthalmic surgeries and diagnosis.

***K*eywords:** *vitreous humor, microrobot, biomechanics, finite element.*

1 Introduction

Vitreous humor is the gel-like fluid that occupies the space between the lens and the retina supporting the eye. It consists of approximately 99% water, 0.9% salts, less than 0.1% heterotypic collagen fibrils, and a hyaluronan network and demonstrates one of the most complex biomechanical properties in the body as presented by Sharif-Kashani et al. (2011). Understanding the biomechanical properties of vitreous humor is essential for the diagnosis of ophthalmic diseases and for developing intraocular surgical instruments.

Conventional methods for characterizing vitreous properties, such as rheometer and atomic force microscopy (AFM), usually require excision and segmentation of the vitreous sample making them nonapplicable *in vivo*. Lee et al. (1992, 1994) studied the viscoelastic properties of bovine, porcine, and human vitreous humors using magnetic bead microrheology. The vitreous samples were cut in parts and properties were characterized. The variation among species and locations was discussed. The porcine vitreous was also studied by Sharif-Kashani et al. (2011) using a stressed-control shear rheometer. The authors found two time scales corresponding to different components of the vitreous.

In this work, a finite element (FE) model was developed to simulate the viscoelastic behavior of the vitreous and its interaction with intraocular surgical instruments. There is a growing interest in using wireless intraocular micro devices such as microrobots for performing microsurgical operations (Ergeneman et al. , 2012; Ullrich et al. , 2013). The model is used to investigate the viscoelastic interaction of wireless microrobots of different geometries with the vitreous. A magnetically-actuated spherical microrobot was used to perform creep experiments inside the vitreous humor as presented by Pokki et al. (2012) to calibrate and validate the FE model.

2 Experimental Measurements and Methods

Creep experiments were carried out in the human eye vitreous from a deceased 75-year-old donor using the experimental method presented in Pokki et al. (2012). A 0.55 mm-diameter NdFeB sphere was actuated by magnetic force to move inside the vitreous humor. Cycled stepwise forces ($\pm 0.46 \mu$N) were applied on the sphere and the position trajectories of the sphere were tracked.

A three-parameter Lethersich model (figure 1a) was used to describe the viscoelastic properties of the vitreous humor. It consists of a Kelvin-Voigt element in series with a dashpot. FE mesh of the vitreous and microrobot was generated using 'Gmsh' as shown in figures 1b, 1c, and 1d. The vitreous body was modeled as a sphere with a diameter of 20 mm and the experimental microrobot was modeled as a small sphere with a diameter of 0.55 mm. One quarter of the system was modeled due to symmetry. FE formulation can be found in Wang et al. (2012). An optimization based method, as presented in Wang et al. (2009), was used to characterize the properties of the vitreous humor.

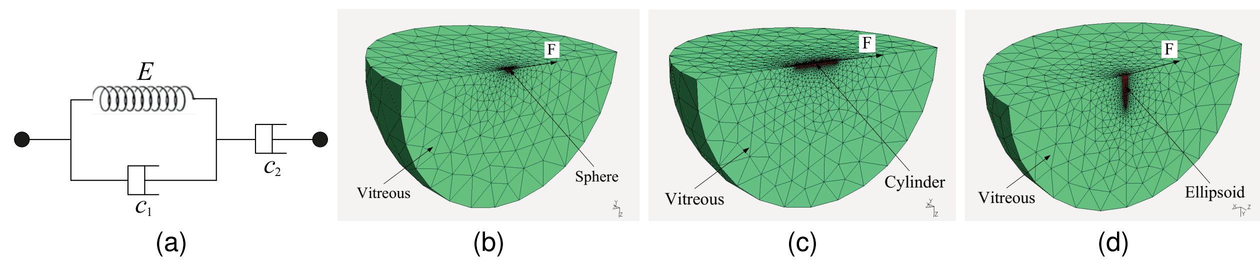

Figure 1: The three-parameter Lethersich model (a), the FE mesh of the vitreous humor with microsphere (b), with horizontal microcylinder (c), and with vertical microellipsoid (d).

Parameter	E (Pa)	c_1 (Pa·s)	c_2 (Pa·s)
Characterized	0.4547	0.1845	5.1454
Lee et al. (1992)	1.27±82%	0.35±60%	2.18±96%

Table 1: Estimated parameters of human vitreous humor and comparisons with published data

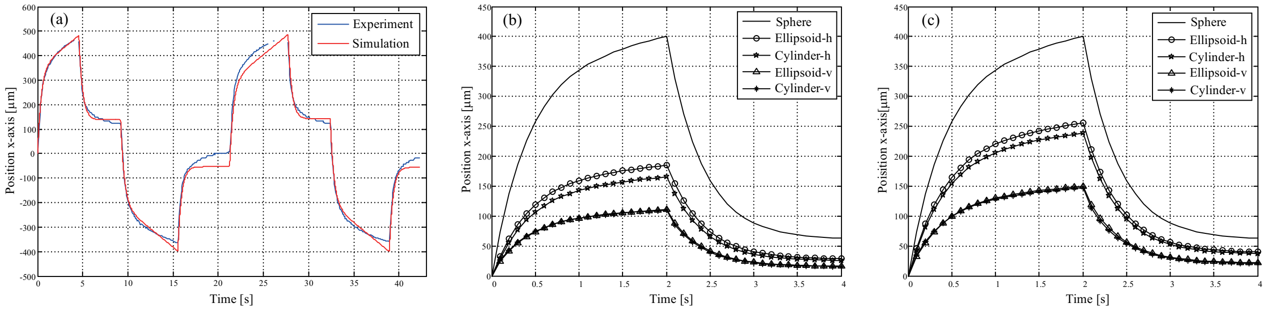

Figure 2: (a) Simulation results compared with experimental measurements, and trajectory comparisons of different shaped microrobots with different orientations: (b) microrobots with same volume and (c) microrobots with same surface area. '-h' and '-v' indicate horizontal and vertical orientations, respectively.

3 Results

The parameters (Young's modulus E, viscous moduli c_1 and c_2) extracted from the model with a comparison to published data are listed in table 1. The simulation results with experimental measurements are shown in figure 2a, where the first cycle of measurements was used for characterization and the remaining cycles were used for validation. The shape-dependent interaction of the microrobot and the vitreous was studied using the FE model and the parameters of human vitreous. Microrobots with a shape of a sphere, cylinder and an ellipsoid were modeled and simulated with different orientations. In horizontal orientation (figure 1c), the longitudinal axis of the microcylinder/ellipsoid was aligned with the moving direction. In vertical orientation (figure 1d), the longitudinal axis was aligned perpendicular to the moving direction. The simulation results are shown in figures 2b and 2c, where all microrobots have the same volume and same surface area, respectively. Among different shaped microrobots, a microsphere moves easier than microcylinder and microellipsoid. Having smooth edges (microellipsoid versus microcylinder) showed improvement in the movement of the microrobot. For different orientations, horizontal orientation is always better than vertical orientation.

4 Conclusions

Knowledge on the biomechanical properties of human vitreous humor is essential in treatment and diagnosis of ophthalmic diseases. A FE model was proposed to simulate the viscoelastic interaction between a microrobot and vitreous humor that will benefit optimizing the design of minimally-invasive ophthalmic instruments.

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