Towards digital twins for ocular applications - a combined physics-based and data-driven approach

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The human eye's complex behavior, influenced by heat transfer and fluid dynamics, presents significant challenges in understanding and modeling ocular physiopathology. While medical data provide valuable insights, their scarcity and noise, along with the multitude of influencing factors, complicate the isolation of individual mechanisms. Developing a robust and accurate digital twin for ocular applications can enhance our understanding of the physiological system by integrating the governing mechanisms and data variability.

This talk presents our continuous efforts [2] to develop a digital twin focused on the thermo-fluid dynamics of aqueous humor flow in the anterior and posterior chambers and its interaction with heat transfer within the eyeball. Aqueous humor dynamics plays a critical role in regulating intraocular pressure and supplying nutrients to surrounding avascular tissues [1]. Additionally, convective currents induced by temperature differences significantly impact topical drug delivery and corneal wound healing processes [4].

Our approach involves developing a full-order physics-based model using the finite element method, rigorously validated against experimental data and numerical studies. To enable real-time feedback, we derived a reliable reduced-order model employing the certified reduced basis method [3]. We conducted forward uncertainty quantification studies using the reduced model with experimentally based stochastic inputs, complemented by global sensitivity analysis to account for variability and noise. The results demonstrate that the reduced-order model significantly reduces computational time while maintaining high accuracy, making it suitable for real-time applications.

The talk will present these developments, discuss their applications in ocular physiology and treatment, and address remaining challenges, including inverse problems and parameter identification. By integrating physics-based modeling with data analytics, we aim to advance the field of digital twins for ocular applications, paving the way for improved diagnostics and personalized treatment strategies.

[1] M. Dvoriashyna, J. O. Pralits, J. H. Tweedy, R. Repetto. *Mathematical Models of Aqueous Production, Flow and Drainage*, pp. 227–263. Springer International Publishing, Cham, 2019.

[2] T. Saigre. *Mathematical modeling, simulation and order reduction of ocular flows and their interactions : building the digital twin of the eye.* Theses, Université de Strasbourg, 2024.

[3] T. Saigre, C. Prud'homme, M. Szopos. *Model order reduction and sensitivity analysis for complex heat transfer simulations inside the human eyeball.* International Journal for Numerical Methods in Biomedical Engineering, **40(11)**, e3864, 2024. doi : https ://doi.org/10.1002/cnm.3864.

[4] S. Yang, J. Zhang, Y. Tan, Y. Wang. *Unraveling the mechanobiology of cornea : From bench side to the clinic.* Frontiers in Bioengineering and Biotechnology, **10**, 2022. doi : 10.3389/fbioe.2022.953590.

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