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PHYSIQUE – CHIMIE INGENIERIE	NANOSCIENCES – PHOTONIQUE – SCIENCES DES MATERIAUX & CARACTERISATION

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PhD subject in CSC program

1. **Title**: Improvement of mechanical constitutive laws of soft tissues under high-speed dynamic configuration with a polyconvex, nonlinear, and anisotropic hyperelastic behavior.

2. **PhD Supervisor**: Prof. François PEYRAUT

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5. **Description of the subject**:

   Numerical simulations are interesting ways to investigate physical phenomenon and to avoid costly experiments. Hence, they allow to predict the mechanical behavior of a structure under severe loadings, and to access data which can be difficult to observe during experiments (A Bracq, 2017). For instance, numerical methods as the finite element method are widely used for investigating high-speed dynamical phenomenon such as impacts. More precisely, powerful numerical models have been developed in the context of biomechanics which predict the occurrence of a trauma when the human body is subjected to severe loadings (J. Shen et al. 2022a, b, S. Meng et al. 2022). To do so, a detailed numerical model of a human body has been developed at ICB laboratory (Roth et al. 2013, Bodo et al. 2017). This numerical model has been built upon the software Altair Radioss, a powerful and now opensource finite element solver (named OpenRadioss) and was initially dedicated to impact applications. Internal organs as well as skeletal structures were modeled using rather standard constitutive laws (viscoelastic, hydrodynamic, elastic, or elasto-plastic laws). Therefore, more representative laws might need to be introduced in this model to better simulate the complex mechanical behavior of the soft tissues.

Indeed, it is mandatory to derive advanced constitutive laws together with relevant material parameters to obtain “BIOFIDELIC” models of soft tissues. Non-linear anisotropic hyperelastic laws are good candidates for modeling the behavior of soft biological tissues reinforced by collagen fibers, such as ligaments, tendons, muscles, or arteries (Peyraut et al., 2009, 2010). Understanding the theoretical background of anisotropic hyperelasticity is therefore of major importance as it concerns a wide range of applications in engineering biosciences, such as health therapeutic, medical prosthesis, ergonomics, or virtual surgery. Another aspect to study is the mathematical framework needed to develop consistent hyperelastic laws. It is for example preferable to use polyconvex invariants for building the strain energy density, as polyconvexity is considered as a prerequisite for ensuring the existence of solutions compatible with physical requirements (Ball, 1976). Polynomial invariants were studied as part of Anh-Tuan Ta's PhD thesis defended in 2014 at UTBM (A.T. Ta, 2014). By using Noether's theorem and the Reynolds operator, the cases of anisotropic hyperelastic materials made of one or two families of fibers were addressed (Ta et al., 2013, 2014). By combining these invariants in a polyconvex manner, several anisotropic hyperelastic laws were then developed in Renye Cai's PhD thesis (R. Cai, 2017). These laws concern fiber-reinforced rubber materials under uniaxial and shear testing (R. Cai et al., 2016), the mechanical response of passive ventricular myocardium (R. Cai et al., 2021), and the modeling of femoral, popliteal, and tibial arteries (R. Cai et al., 2017, 2022).

The development of such biomechanical models in the framework of high-speed dynamic loadings is not straightforward, and the PhD student will investigate and tackle several issues such as:

- Investigation of the mechanical parameters of the involved materials in a biofidelic manner to obtain significant and realistic results,
- Implementation of polyconvex anisotropic hyperelastic laws (selected from the literature or originally developed) in a biomechanical model developed in our lab,
- Validation of the implemented polyconvex anisotropic hyperelastic laws via experimental data,
- Extension of the anisotropic behavior until the rupture domain, in order to investigate damage to finally explore the injuries that can occur in human organs under impacts.

To summarize, the PhD student will have to develop hyperelastic, anisotropic, polyconvex and biofidelic laws, implement them using the finite element method, and finally carry out simulations in the context of high-speed impact. Taking all these aspects into account is a challenge, as it requires dealing with many levels of non-linearity in the context of high-speed dynamic impact.

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