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

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PhD subject in CSC program

1. **Title**: Polyconvex anisotropic hyperelastic behavior of soft tissues under high-speed impact loadings

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5. **Description of the subject**:

   Numerical simulations are interesting ways to investigate physical phenomenon and to avoid costly experimental devices. In a mechanical framework, it allows predicting the behavior of a mechanical structure under severe loadings, and access to data which can be difficult to observe during experiments (A Bracq, 2017). As an example, numerical simulations like finite element methods are widely used for the understanding of high-speed dynamics phenomenon such as impact mechanics. In the framework of biomechanics, this numerical method has allowed developing powerful models, able to predict the occurrence of a trauma when the human body is subjected to severe loadings (J Shen et al. 2022 a, b, S Meng et al. 2022).

   To obtain a “BIOFIDELIC” model, it is necessary to implement appropriate soft tissues constitutive laws, with correct material parameters. Especially, in the context of numerical biomechanics, specific parameters must be implemented for a given constitutive law, as already conducted in our lab for the development of a human body model (Roth et al. 2013, Bodo et al. 2017). This numerical model was initially developed for impact applications using the code “Radioss” ©. Internal organs as well as skeletal structures were modelled using linear or non-linear laws (visco-elastic, hydrodynamic, elastic or elasto-plastic laws).

More complex laws can be implemented in the model, to enhance the biofidelic mechanical response. For example, non-linear anisotropic hyperelastic laws could be used as in (Peyraut et al., 2009, 2010) for modeling the behavior of soft biological tissues reinforced by collagen fibers (ligaments, tendons, muscles, or arteries). Understanding the theory of anisotropic hyperelasticity is therefore of major importance. It concerns a wide range of applications in engineering biosciences such as in health therapeutics, 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, polyconvexity being considered as a prerequisite for ensuring the existence of solutions in compatibility with physical requirements (Ball, 1976). Polynomial invariants were studied as part of Anh-Tuan Ta's 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 fibers families were addressed in (Ta et al., 2013, 2014). By combining these invariants in a polyconvex manner, several anisotropic hyperelastic laws were then developed in Renye Cai's thesis defended in 2017 at UTBM (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 nonlinear behavior of anisotropic materials modeled with hyperelastic laws will be investigated by considering several mechanical phenomena which are involved when these structures are submitted to high-speed dynamic loadings. Such a study, which has already been carried out for an isotropic hyperelastic material with dynamic impact in (Z.-Q. Feng, et al., 2006), will be extended in this thesis to the case of an anisotropic hyperelastic material.

Therefore, the PhD student will have to investigate and achieve several topics linked to mechanical engineering in the context of biomechanics, such as:

- The investigation of mechanical parameters of the involved materials (such as biological tissues) has to be conducted in a biofidelic manner to obtain significant and realistic results with the biomechanical model.
- The polyconvex anisotropic hyperelastic law (selected from the literature or originally developed) will be implemented in the in-house finite element code FER developed by Prof. Feng, and by using a biomechanical model already developed in our lab. Validation must be conducted against experimental data of the literature.
- An extension of the anisotropic behavior can also be considered until the rupture domain, in order to investigate damage to finally explore the injuries that can occur in human organs under impacts.

Finally, this PhD thesis is defined by the development of numerical biofidelic models, representative of some soft tissues of the human body and simulations using complex and nonlinear constitutive laws. The context of this thesis is an indeep understanding of the mechanical behavior of soft tissues, and good knowledge of mechanical phenomenon and materials are expected to investigate the specificity of soft tissues engineering in the context of large strain, and under high-speed impact loading.

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