PhD Research Proposal
Cofund « Artificial Intelligence for the Sciences »
PSL University - 2022-2025

Transfer learning in biomechanics

1. Names and affiliation of co-supervisors

David Ryckelynck[(a)], Etienne Decencière[(b)], Laurent Corté[(a)]

The resumés of the co-supervisors are attached to this proposal.

2. Name and short description of the affiliated laboratoryies

(a) Centre des Matériaux, Mines ParisTech PSL University
(b) Centre de Morphologie Mathématique, Mines ParisTech PSL University

The PhD student will be hosted in both Centre des Matériaux and Centre de Morphologie Mathématique of Mines ParisTech PSL University.

The Centre des Matériaux, located at Evry, is a laboratory associated with the CNRS, employing around 200 people including 30 researchers, 50 ITA, 85 PhD students and 11 Post-Doctoral researchers. Research concerns biomaterials, engineering materials, microstructural characterization, numerical modeling at various continuous scales and related data science.

The Centre de Morphologie Mathématique, located at Fontainebleau, is a laboratory specialized in image processing. The research work conducted in this laboratory is based on mathematical morphology and deep learning. The fields of application are varied: multimedia, material sciences, electronics, bioimaging, medicine, industrial control.

A recommendation letter from the both directors is attached to this proposal.

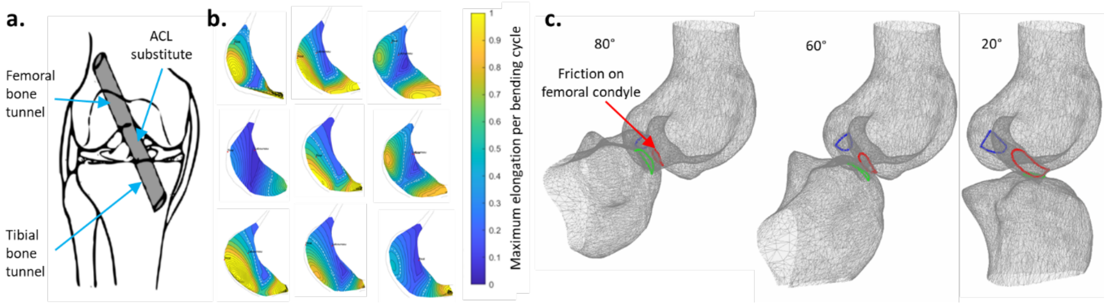
3. Name of the doctoral school of affiliation

Ingénierie des Systèmes, Matériaux, Mécanique, Énergétique
Mines ParisTech PSL University

5-Main discipline of the thesis: Mechanics, CNU 60

6-Description of the subject

[Transfer learning in biomechanics]
High-dimensional transfer learning for personalized biomechanical modeling in surgery planning: application to anterior-cruciate ligament reconstruction



a. Schematic representation of the reconstructed anterior cruciate ligament [1]; **b.** Maps showing the femoral condyle with the maximum elongation undergone depending on the position of the insertion point. Experimental data from Ligagel project [2] [unpublished data]; **c.** 3D images showing the evolution of contact on an implanted ACL substitute (red region) [2] [D.Maeztu-Redin thesis, unpublished data].

Numerical modeling offers unprecedented possibilities for surgery planning by allowing quantitative patient-specific predictions, therefore reducing the risks of complications and improving the safety of the patients [3]. While the first generation of models are solely based on bioimaging data, numerous surgical problems necessitate a more complex description that takes into account the mechanics and kinematics of the tissues and implants of interest [4, 5], with patient-specific images as input data. The reconstruction of the Anterior Cruciate Ligament (ACL) in Fig. 1a., which is the most frequent ligament injury (incidence rate 1/3000), is an excellent illustration of this challenge. Recent works have shown that friction against the cartilage of the femoral notch and condyle is a major cause of failure for reconstructed ACL. The occurrence and intensity of friction is highly sensitive to the location of the femoral and tibial insertion points chosen by the surgeon (Fig. 1b) and to the local bones shape. Such contact problem is extremely difficult to anticipate as it depends not only on the geometry but also on the kinematics of each knee (Fig. 1c). Today, the image-based biomechanical modeling procedure is far away too slow for any practical application to patient-specific modeling in view of surgery planning.

Our project proposes to tackle this issue by associating Artificial Intelligence approaches, model reduction and image-based biomechanical modeling to develop efficient numerical models for ACL reconstruction. The objective is three-fold: (i) to provide a clinically-relevant model applicable to fast surgical planning; (ii) to provide a deeper understanding of the damaging mechanisms of reconstructed ligaments; (iii) to develop deep transfer learning methods for image-based modeling in biomechanics [6, 7, 8, 9]. For that, input data coming from different sources will be used: radiographic data [10, 11], magnetic resonance images [12, 13], experimental data on animal models [2], data on the variability of surgeon accuracy.

The project will benefit from an established collaboration with the consortium of the LIGAGEL project [2], which aims at developing novel artificial ligaments for ACL reconstruction [14]. This will provide access to complete data sets including 3D biomechanical simulations, 3D imaging and kinematics for both sheep (see for instance Fig. 1b-c) and Human knee joints as well as post-operative observations of ligament and cartilage damage in the case of animal studies. This project will be a success if patient specific digital images and hyperelastic data, with different source domains, are merged in a fast image-based modeling chain, with a simulation speed up of 100.

In high-dimensional transfer learning, dimensionality reduction is one of the most important ways to preserve the discriminant information for subsequent classification [15] or for model order reduction via a ROM-net[16]. In reduced order models, both deep learning and physical equations are coupled in a single modeling procedure. It achieves transfer learning. The main advantage of transfer learning is its ability to reuse data related to various source domains, here biomechanics and image classification, when it is expensive or impossible to re-collect the needed training data for the target domain [6, 7, 8, 9]. Recent advances in U-nets [17, 18] and in multimodal autoencoders [19] that extract a common latent space from various sources of data, will certainly foster fast image-based reduced predictions with transfer learning. A particular attention will be given to the description of the sensitivity to the femoral and tibial insertion points, to the bones geometry and to the mechanical behavior of the ligament substitute.

The PhD student will join the "Artificial Intelligence for the Sciences" training program. All observational data and numerical being already available, we are confident that several papers will be published in 3 years. More over, we already have a good experience in U-nets [18] and in transfer learning via ROM-nets [16] for mechanical modeling.

References

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7. Possible international mobility during the thesis

The PhD student will have the opportunity to visit the Berkeley Institute for Data Science (https://bids.berkeley.edu). We plan to work with Stefan van der Walt (stefanv@berkeley.edu) on reproducible science in machine learning.

8. Expected profile of the candidate

The candidate for this PhD thesis is expected to have a master's degree in biomechanics, or a master's degree in machine learning, or a master's degree in computer vision. He will have to demonstrate a very good knowledge of python programming.

9. Contact person for more information

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