# Patient-Specific Finite Element Modeling of the Diabetic Foot

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## Introduction

Diabetic feet are at risk of ulceration due to the arteriopathy and neuropathy associated with diabetes mellitus. Internal overstresses within the soft tissues, especially nearby bony prominences are likely to evolve into a deep foot/toe ulceration which, if not treated rapidly and properly, can lead to an amputation. Finite Element (FE) biomechanical modeling of a patient's foot makes it possible to predict the magnitudes of internal stresses from the measurements of external pressures applied at the skin surface. This mechanical analysis relies on a geometrical representation of the foot's shape, called "Finite Element mesh". A framework for automatic generation of patient-specific FE meshes of the diabetic foot is presented here.

## Methods

Subject specific Finite Element mesh generation is a complex task which, in most cases, requires an expert operator to control sub-domain representation, choice of element type, layout and refinement. This operation is time-consuming and can hardly be put into practice when a large number of models need to be generated for large scale studies. In situations where automatic mesh generation is unsuitable, the FE mesh registration technique, known as Mesh Match and Repair (MMRep), has been proposed for quickly creating a subject-specific mesh by fitting a predefined template – or Atlas – mesh onto the patient foot's shape [1]. The lengthy and careful assembly of the Atlas mesh is carried out only once. For each patient undergoing biomechanical study, the shape of both the skin and bones of the Atlas mesh is adapted, or "registered", to the skin and bone surfaces recovered from the patient's medical images (e.g. CT scan or EOS). A three dimensional non-linear registration function **R** is computed between the Atlas and patient spaces so as to minimize a "registration energy term" **E**, defined as:

$$\mathbf{E}(\mathbf{R}) = \sum_{s \in AtlasSkin} d(\ \mathbf{R}(s),\ PatientSkin\ ) + \sum_{b \in AtlasBone} d(\ \mathbf{R}(b),\ PatientBone\ ) \qquad (1)$$

In (1), *AtlasSkin* and *AtlasBone* are the sets of surface nodes of the Atlas mesh lying on the skin and bone surfaces respectively. *PatientSkin* and *PatientBone* are the equivalent surfaces reconstructed from the patient's medical images. Finally, the operator **d** computes the Euclidean distance between a 3D point and a surface. Once the registration function **R** has been estimated, its 3D deformation field is applied to the whole Atlas model and the anatomical structures possibly represented within (muscles, fat layers, bones, but also tendons, fascia and joints). The assumption is made that a global deformation computed on skin and bone surfaces alone can be used to infer the shape and location of other structures as well. A shortcoming of this approach is that the non-linear registration is likely to alter the regularity and quality of the Atlas mesh elements. Indeed, large nodal displacements produced by the deformation **R** can result in distorted mesh elements which in turn may affect the numerical accuracy of the subsequent FE analysis [2]. Such distorted elements must thus be "untangled". A specific mesh untangling algorithm has recently been validated [1,3] for this crucial purpose.

## Results

The technique was successfully applied on two CT exams from which accurate FE meshes of the individuals' feet could be produced within 5 minutes. Mesh regularity and quality were recovered while preserving the accuracy of the surface representation.

## Discussion

The use of an Atlas model of the foot helps overcome possible lacks of information by extrapolating the *a priori* knowledge carried by the generic mesh. However, care must be taken while defining the Atlas mesh especially when dealing with cases of amputations or excessively deformed feet (Charcot's foot). A small set of dedicated Atlas meshes might have to be defined e.g. one per amputation type.

## Clinical relevance

MMRep seems well suited in a clinical context where the reconstructed anatomical surfaces can be partially imaged or have a poor resolution (merged structures).

## Acknowledgements

The authors wish to thank the ANR TecSan IDS project for its financial support.

### Conflict of Interest

None.

## References

[1] Bucki M. *et al.*, Med. Image Anal. 14:303-17, 2010
[2] Knupp P. Int. J. Numer. Meth. Eng. 48:1165–85, 2000.
[3] Bucki M. *et al.*, Eng. Comput. 27:285-97, 2011