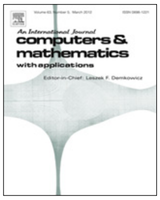
ARTICLE IN PRESS

Computers and Mathematics with Applications ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa



An automated workflow for the biomechanical simulation of a tibia with implant using computed tomography and the finite element method

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ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form 18 May 2015
Accepted 6 June 2015
Available online xxxx

Keywords:
Adaptive volume-mesh generation
Hanging nodes
Finite element method
Patient-specific simulations
Fractured tibia with implant

ABSTRACT

In this study, a fully automated workflow is presented for the biomechanical simulation of bone–implant systems using the example of a fractured tibia. The workflow is based on routinely acquired tomographic data and consists of an automatic segmentation and material assignment, followed by a mesh generation step and, finally, a mechanical simulation using the finite element method (FEM). Because of the high computational costs of the FEM simulations, an adaptive mesh refinement scheme was developed that limits the highest resolution to materials that can take large amounts of mechanical stress. The scheme was analyzed and it was shown that it has no relevant impact on the simulation precision. Thus, a fully automatic, reliable and computationally feasible method to simulate mechanical properties of bone–implant systems was presented, which can be used for numerous applications, ranging from the design of patient-specific implants to surgery preparation and post-surgery implant verification.

1. Introduction

1.1. Clinical relevance

Bone healing disturbances are clinically and socio-economically highly relevant: 10%–15% of osteosynthesis show signs of bone healing disturbances that need further diagnostic and therapeutic efforts to achieve fracture union.

The “diamond concept” [1], which constitutes the current paradigm of fracture therapy, considers biological, cellular, mechanical and matrix components as equally important prerequisites for successful fracture healing.

Meanwhile, several concepts are available to improve the biological, cellular and matrix components in cases of impaired fracture healing. The mechanical components and their contribution to an impaired fracture union can only be analyzed on a very coarse grid based largely on the results of imaging procedures like computed tomography (CT) and conventional radiography. The dynamic nature of the mechanical components, like the osteosynthesis technique, the bone quality, and

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http://dx.doi.org/10.1016/j.camwa.2015.06.009
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Please cite this article in press as: T. Dahmen, et al., An automated workflow for the biomechanical simulation of a tibia with implant using computed tomography and the finite element method, Computers and Mathematics with Applications (2015), http://dx.doi.org/10.1016/j.camwa.2015.06.009

the loading conditions (e.g. body weight, the patient's ability to reliably perform partial weight bearing concepts), are almost completely excluded from analysis.

Personalized decision making and therapy is an emerging issue in the field of orthopedic trauma surgery. Imaging studies are a mainstay of decision making considering the patient's history (including compliance, etc.) and patient factors relevant to prognosis, e.g. smoking history, steroids, and diabetes. Within this framework, general medical knowledge, e.g. knowledge derived from clinical studies and evidence-based medicine procedures, is augmented with a variable amount of personal experience and opinions of the physician.

However, traditional medical decision making is an inductive process. From the methodological point of view, truly personalized approaches to non-union therapy require to integrate general medical evidence, the general laws of biomechanics, information derived from imaging procedures and the situation of the individual under consideration in a systematic and reproducible manner. Especially imaging studies do carry relevant amounts of unutilized information.

The tools necessary for further development and the scientific work-up of personalized medicine concepts, as well as for the implementation into the clinical routine in orthopedic trauma surgery, are currently not available and need to be developed.

In this work, a method is presented to simulate the stresses and strains occurring in bone–implant systems, using the method of finite elements (FEM). Hereby, the simulations are directly based on the tomographic data, in the sense that the imaging data is converted without intermediate surface representation to an FEM mesh.

1.2. *State of the art*

FEM simulation originates from engineering science, in which it is also well established. As elaborated in [2], the approach was first introduced to the field of orthopedics in 1972 [3]. Since that time, FEM models have been increasingly used for three main purposes: (i) for the design and pre-clinical analysis of prostheses; (ii) to obtain fundamental knowledge about musculoskeletal structures; and (iii) to investigate time-dependent adaptation processes in tissues (i.e., growth, remodeling and degeneration) [4]. Successful three-dimensional (3D) finite element modeling has been applied to several different prostheses, such as the hip [5–8], the knee [9], the metacarpophalangeal joint [10], and the shoulder [11]. Common to this line of work is that adaptive mesh generation schemes are widely used, but the mesh generation is based on a computer-aided design (CAD) model of the implant, not on a tomogram.

More recently, FEM simulation has been applied to meshes directly generated from tomograms. A review of different mesh generation schemes with uniform resolution was presented in [12]. In this line of work, the focus shifted to the analysis of small sections of bone that were assumed to be representative. These analyses were then used to assess the overall bone strength [13]. This is also evident in works concerning microstructural FEM analysis, which offers a powerful tool to determine bone stiffness and strength [14].

In order to generate FEM meshes from tomograms, two conversion steps are required. The tomograms need to be segmented in order to assign material properties to the grayscale values. Additionally, the mesh needs to be generated. The topic of segmentation has received much research interest in the past; a relatively recent overview of the field is given in [15]. In this study, a combination of filtering with edge-enhancing non-linear anisotropic diffusion and subsequent adaptive thresholding was implemented, which is one of the standard approaches to the problem.

Besides the segmentation, the tomographic data needs to be converted to a mesh. However, most of the previous work on the generation of FEM meshes starts with surface representations of the model that is typically used in CAD applications. A relatively recent overview of this approach for the case of hexahedral meshes is given in [16]. In order to apply those well established methods to tomographic data, a surface must be extracted from the volume as an intermediate representation. This is typically done by generating iso-surfaces, for example using the marching cubes algorithm [17]. A mesh can then be generated from the iso-surface using standard methods. One method using tetrahedra is presented in [18]. An example for the case of hexahedral meshes is presented in [19]. Because this method does not rely on hanging nodes, great care has to be taken to ensure the connectivity of the mesh. The mesh is refined adaptively using a template strategy to closely match the iso-surface.

The work closest related to the current study is given in [20], in which FEM simulations are performed for a real femur specimen and compared with experimental measurements. However, as with most related work, the used tetrahedral meshes are generated by meshing a 3D surface of the bone shape obtained from the tomographic data in a preprocessing step. These meshes are smaller by a factor of 50 compared with the mesh for the bone–implant system considered in the current study. In a second step, in [20], the mechanical properties of inhomogeneous bone tissue are computed on the basis of the density information derived from the CT dataset, and are mapped via interpolation of the given hexahedral image data onto the generated tetrahedral meshes. The required remapping step obviously leads to some degree of resampling error.

An alternative approach is the finite cell method [21] that also shows promising results when applied to clinical CT data. As most related work, the finite cell method is based on the extraction of a surface representation of the model, prior to the mesh generation. A quantitative comparison to our method concerning simulation accuracy, memory requirement and simulation time should be performed in the future.

Different from CAD data, for which the surface representation can be considered as a ground truth, the iso-surfaces used in those studies were extracted from imaging data of limited resolution, using an iso-value that is necessarily chosen with some degree of arbitrariness. The current study therefore questions the hypothesis that a good FEM mesh should

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