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An optimization algorithm for individualized biomechanical analysis and simulation of tibia fractures

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ABSTRACT

An algorithmic strategy to determine the minimal fusion area of a tibia pseudarthrosis to achieve mechanical stability is presented. For this purpose, a workflow capable for implementation into clinical routine workup of tibia pseudarthrosis was developed using visual computing algorithms for image segmentation, that is a coarsening protocol to reduce computational effort resulting in an individualized volume–mesh based on computed tomography data. An algorithm detecting the minimal amount of fracture union necessary to allow physiological loading without subjecting the implant to stresses and strains that might result in implant failure is developed. The feasibility of the algorithm in terms of computational effort is demonstrated. Numerical finite element simulations show that the minimal fusion area of a tibia pseudarthrosis can be less than 90% of the full circumferential area given a defined maximal von Mises stress in the implant of 80% of the total stress arising in a complete pseudarthrosis of the tibia.

1. Introduction

Delayed union and nonunion of fractures of the long bones remain a challenging problem in orthopedic trauma surgery. Surgical resection of the nonunion and transplantation of autologous cancellous bone are the mainstay of therapy often resulting in bone defects of variable size. Open debridement of the nonunion requires wide exposure of the compromised bone, thus further impairing the local vascular supply. Adhering to the principles of the diamond concept (Giannoudis et al., 2007), which considers biological factors, e.g. local vascular supply and osteogenic cells, equally important as a mechanically stable osteosynthesis, surgical approaches to a nonunion need to be developed that maximally preserve local biological factors.

However, ‘mechanical stability’, i.e. the patient being mobilized with full weight bearing, is the attempted endpoint of nonunion therapy. To achieve this endpoint, the implant needs to resist the stresses and strains occurring during the remodeling process of the bone until, finally, the bone has sufficiently been remodeled to transfer the loads by itself. Given the load adaptive properties of bone, we hypothesize that it might be possible to achieve the endpoint of mechanical stability without filling the complete nonunion site with cancellous bone, but that less than full circumferential cancellous bone transplantation might be sufficient. This question needs to be answered individually for each nonunion as fracture patterns and nonunion patterns are highly variable. Apparently, this approach primarily applies to aseptic and atrophic nonunion with an intact osteosynthesis in situ.

Prior to the clinical implementation of an individualized minimally invasive approach to nonunion therapy, tools need to be developed that allow an evaluation of the biomechanical properties of the individual nonunion with respect to the stresses and strains arising in the implant, the screw–bone interfaces, and the fracture area for different degrees of bone union and different loading conditions during the mobilization of the patient.

We consider numerical simulations of finite element models working directly on computed tomography data sets from the individual patient, which are acquired during the routine workup of a nonunion, as the most suitable tools to approach this question.

In this work, an algorithmic workflow for the extraction of an individual finite element model from routinely acquired computed tomography data sets, which allows numerical simulations of different degrees of nonunion consolidation, is presented. Part of this workflow is an algorithm designed in such a way that the minimal amount of fracture union necessary to allow physiological loading (i.e. mobilization of the limb) without subjecting the implant to stresses and strains that might result in implant failure is determined. The algorithm is then applied to a model system of a tibia pseudarthosis as proof of its

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clinical applicability and to demonstrate a first in vitro proof of concept of the hypothesis that less than full circumferential transplantation is sufficient to achieve a mechanically stage union of tibia pseudarthroses.

2. Methods

2.1. Preparation of the fracture model

An AO type 42-B1.1 was implemented in a tibia model (Sawbones Europe, Malmø, Sweden). The fracture classification AO type 42-B1.1 represents multifragmentary diaphyseal fractures of the tibia with a spiral wedge third fragment that, once reduced, maintains the contact between the proximal and distal fragments (Ruedi et al., 2007).

To improve the radiographic visibility of the bone model, the surface of the sawbone was treated with zinc spray. The fracture was fixed using a 14-hole titanium distal tibia-locking compression plate (anatomical LCP, Synthes, Oberdorf, Switzerland).

2.2. Tomogram of the fracture model

A computed tomography (CT) scan of the fracture model was acquired (Somatom Definition Flash, Siemens, Germany). The resulting tomogram is a series of 726 single CT images in the `uint12` data format. These 12-digit binary numbers can be mapped linearly to the Hounsfield scale. The slice thickness of the CT data set is constant with a distance of 0.6 mm between two pictures. The images are square-cutted with 512 pixels in height and width. The pixel spacing is also equal inside all images with rounded off 0.318 mm.

2.3. Image segmentation

The segmentation process is based on the anisotropic diffusion algorithms for image processing (Weickert, 2005) in combination with edge-preserving regularization and edge detection techniques (Perona and Malik, 1990; Charbonnier et al., 1997), cf. Fig. 1. In a challenging semi-automatic segmentation process, we have also marked the pixels of the fracture area of the bone. For the numerical simulations, we have set the material properties of the fracture area to the material properties of soft tissue (Chen et al., 1996). In another challenging semi-automatic segmentation process, the pixels of the pseudarthrosis area inside the bone have been marked. As well for the numerical simulations, the material properties of the pseudarthrosis area are also set to the material properties of soft tissue (Chen et al., 1996).

After the segmentation, all relevant image data is mapped to a volume-mesh for the finite element simulations, which contains nearly the possible maximum of the information from the computed tomography. This means that the volume-mesh covers the structure of the bone–implant system nearly without any artifacts from the segmentation process. For this purpose, all segmented pixels will be transformed to volume pixels (voxels) with the help of the slice thickness. The grayscale value of each pixel will be mapped on the barycenter of the corresponding voxel. Fig. 3 shows the mesh for the artificial bone with fracture and implant.

2.4. Coarsening process

To accelerate the computations and to require less memory, the volume-meshes are made coarser with respect to the volume fractions of the particular materials and their properties. The coarsening algorithm operates on the 2D image plane because the tomogram has an anisotropic resolution in the direction of the image stack. For each level of coarsening, the algorithm moves a level $\times$ level-pixel window through the segmented images and combines the pixels inside the window to a new larger pixel, cf. Table 2. This process can be interpreted as a 2D box filter for image downsampling. To determine the material properties of the new pixel, the material properties inside the window are averaged by an arithmetic mean and subsequently cut with an appropriate threshold value.

2.5. Volume-mesh generation

The image stack from the computed tomography raw data as well as from the coarsening process can be easily transferred to volume-meshes by limiting the polyhedral topology to hexagons. For each voxel in the meshes, a cuboid hexagon is created that represents the extent of this voxel. The material information of every voxel is stored in the corresponding mesh cell to the voxel.

To derive an empirical elasticity–bone density relationship for the artificial bone, the grayscale values of the CT imaging data are mapped to the Hounsfield scale and subsequently to the local bone properties (Hvid et al., 1989; Rho et al., 1995; Zannoni et al., 1998). This was done in analogy to the approach for real bones by means of a mapping based on a power law relationship and a calibration phantom (Taddei et al., 2004; Helgason et al., 2008; Cattaneo et al., 2001). The apparent density as densitometric measure was used to compute the real density, Young's modulus, and Poisson's ratio.

2.6. Optimization algorithm

The algorithm seeks the minimal amount of fracture union necessary to allow physiological loading (mobilization of the patient) of the limb without subjecting the implant to stresses and strains that might result in an implant failure. For ease of computation and comparability von Mises stress was chosen as control parameter. Although a dimensionless parameter based on the von Mises stress is computed at low computational costs while providing the essential information for the intended proof of concept that less than complete fusion of a nonunion is sufficient to keep the stress in the implant within subcritical boundaries.

The boundary conditions for the optimization algorithm are given by a complete union of the pseudarthrosis and by a complete nonunion of the pseudarthrosis. Initially, a *worst case* scenario is computed, i.e. the material parameters of the region marked as the nonunion area during the segmentation process are set to the parameters of soft tissue (Chen et al., 1996). With this boundary condition, the maximum possible von Mises stress arising in the implant (with a given set of loading parameters) during the optimization process is defined.

The optimization process starts from a state of complete union of the pseudarthrosis, i.e. the material parameters of the nonunion area are set to cortical bone. The aim of the optimization procedure is to stepwise approach the minimum amount and location of bone bridging over a nonunion that will protect the implant (in this case a plate osteosynthesis) from overloading. The criterion when the algorithm moves to the next iteration needs to be defined a priori. This criterion is called a stop criterion. The stop criterion was set to 20% of the maximum von Mises stress arising in the current step of the algorithm, i.e. if a mesh in the area of the nonunion carries less than 20% of the load it is considered omittable. For this proof of concept study the value of 20% for the stop criterion what is chosen arbitrarily assuming that nonunion area cells sharing less than 20% of the total load can be eliminated such that the load can be dissipated over the neighboring cells. This procedure is repeated until no more nonunion area cell can be eliminated. With the number of unfilled areas increasing with every run of

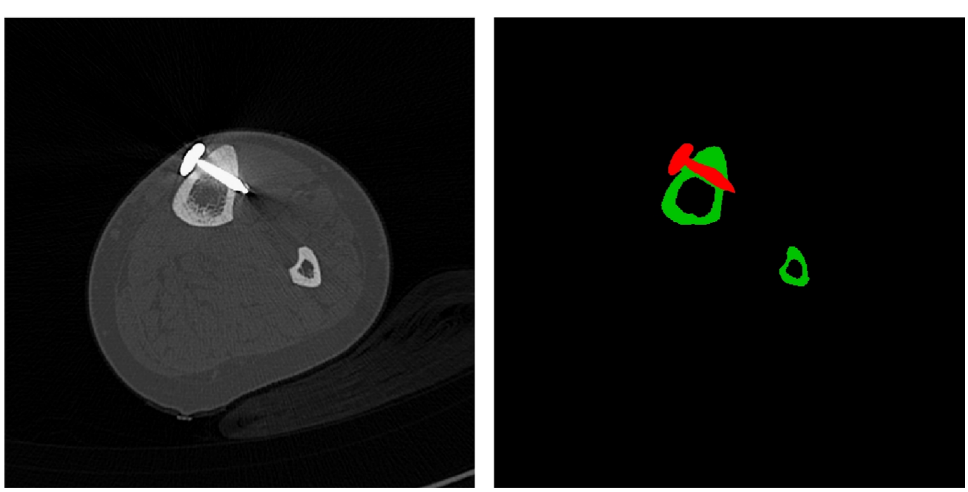

Fig. 1. Original computed tomography image (left); results of the segmentation process (right).