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A simulation-based virtual laboratory for the determination of minimal fusion areas in tibia pseudarthrosis

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Introduction

Delayed union and non-union of fractures remain a challenging problem. Surgical resection of the non-union and transplantation of autologous bone are the mainstay of therapy often resulting in bone defects of variable size. However, mechanical stability, i.e. the patient being mobilized with full weight bearing is the attempted endpoint of non-union therapy. We hypothesize that it is possible to achieve the endpoint of mechanical stability with less than full circumferential cancellous bone transplantation and demonstrate this using a new simulation-based virtual laboratory.

Methods

The goal of this proof-of-concept study is the establishment a virtual lab for the determination of the minimal fusion area of tibia pseudarthrosis to achieve mechanical stability. The basic component of our virtual lab is the generic generation of bone models based on computed tomography scans of human cadaveric specimens via segmentation, anatomical landmarks combined with a Procrustes analysis and a principal component analysis (PCA). These models represent also different anthropometric factors and in a second step are fitted with varying fracture morphologies based on the AO/OTA fracture classification using fracture models generated with a free-form software. In a computer-aided design step, the models of the fractured bones are provided with appropriate implants and passed to a finite element (FE) based optimization algorithm for the detection of the minimal amount of fracture union necessary to allow physiological loading. In contrast to previous approaches, cf. [1,2], this new virtual lab allows a significantly extended analysis of the mechanical stability including multiple loading scenarios from the patient's daily life combined with surgically relevant cancellous bone transplantation sizes and different healing stages reflected by appropriate material parameters. As a second major extension, the local micromechanics in the fracture gap and their medically reasonable constraints are considered in the optimization in addition to the implant stress.

Results

The virtual laboratory presented here allows the detection of the minimal area of a tibia pseudarthrosis that needs to be filled for a mechanically valid fusion under various loading scenarios representing different weight bearing regimes. The consideration of the healing window in the fracture gap as a second parameter in addition to the implant stress leads to improved results compared to simulations that consider only one optimization criterion. Nevertheless, minimal fusion areas can be less than 80% of the full circumferential area depending on individual fracture morphology, treatment and weight bearing regime.

Discussion

Generic model generation eliminates the time-consuming step of segmenting a fractured and treated tibia from the clinical imaging, while the differences between generic and patient-specific models in the simulation results remain acceptable. This new virtual lab show that minimal fusion areas can be determined also considering patient-specific aspects where an extension to other bones is possible.

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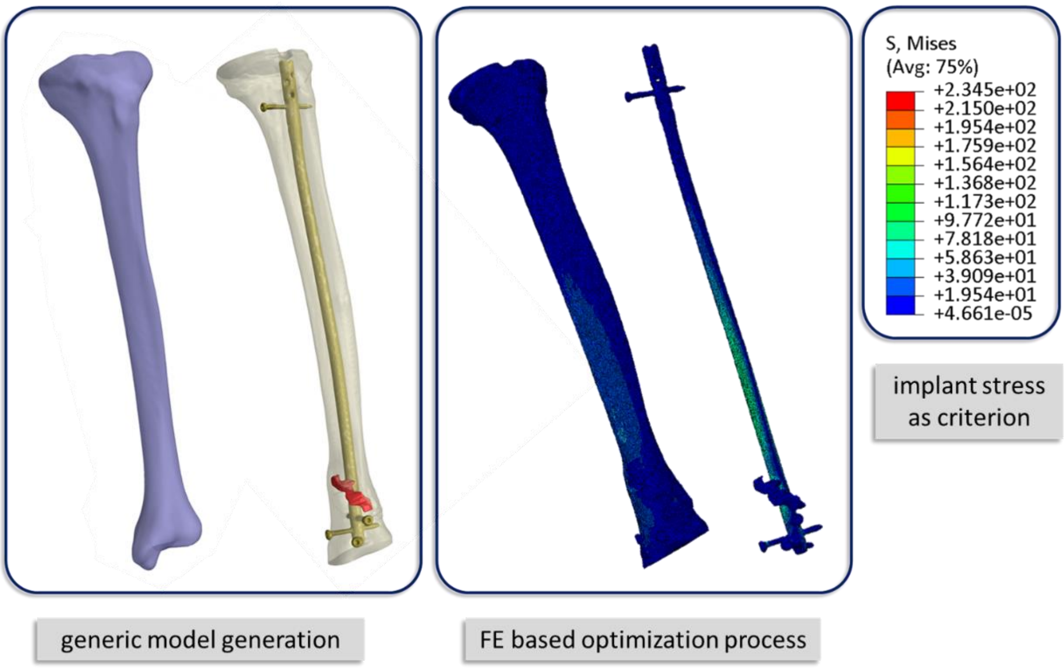

Figure 1: This figure illustrates individual steps from the virtual process from a generic tibia model to a von Mises stress analysis of the implant.