A 3D Simulation System for Hip Joint Replacement Planning

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Abstract— **We present a tool for hip joint replacement planning that allows the surgeon to rank the long-term stability of an implant, and we show the application of this tool in a clinical routine setting. The tool allows the surgeon to predict the load transmission of an implant to the patient-specific bone. It is used to select of a set of available implants the one that most closely replicates the physiological stress state in order to avoid stress shielding. Advanced simulation technology is combined with 3D visualization options to provide quick and intuitive understanding of the generated results. Interactive feedback rates and intuitive control mechanisms facilitate the finding of an optimal implant shape with respect to the patient's specific anatomy. By restricting to a predetermined implant position, which is in accordance with the selected position in a real surgery, the surgeon can quickly analyze a number of different implants under varying load conditions.**

Keywords— **Implant Planning, Orthopedics, Computational Steering, Finite Elements, Stress Visualization.**

I. INTRODUCTION

We present a 3D planning tool for total hip joint replacement surgery, which allows during a preoperative design loop for a patient-specific selection of the optimal implant design. The clinical relevance of such a planning approach is due to the well known fact that an essential determinant factor for the long-term stability of an endoprosthesis is the physiological load transmission from the implant to the adjacent bone stock. One major issue in joint replacement surgery is the effect of stress shielding, i.e., the removal of stress from certain regions of the bone, caused by the stiffening of the bone by the implant and an unphysiological load transfer from the implant to the bone. Due to the bone's physiological reaction to changed stress patterns, stress shielding may lead to adaptive remodeling and increased bone loss, with the consecutive effects of osteopenia, fracture and aseptic loosening [1, 2]. Therefore, an optimal implant should provide bone stress patterns that closely replicate the preoperative physiological stress state.

The main objectives for a preoperative implant planning tool are thus to simulate the mechanical response of a patient-specific bone to a load that is applied to the implant, and to find of all available implant designs and sizes the one that results in the most physiological stress distribution. The challenge in developing such an analysis tool results from the complexity of simulating the stress due to exerted forces in a physically correct way and at calculation times that allow for an interactive implant selection. Furthermore, such a tool is highly demanding on advanced visualization techniques, because it requires simultaneous visualization of surface and dynamic volume structures at interactive rates.

In the clinical practice today, the preoperative planning for the selection of an implant for hip joint replacement is performed on a 2D X-ray of the patient's hip joint, and the surgeon is only able to select on this image the approximately best fitting size of an endoprosthesis using simple, transparent template sheets with the outlines of the implants. Therefore, the physiological response of the bone to the implant is not considered and rotational misalignment cannot be controlled.

To overcome these problems new approaches were pursued in the last years to use geometric 3D information from patient-specific CT data [3, 4, 5], and to integrate this information into virtual 3D planning systems. These systems, however, do not perform any reliable biomechanical simulation and only help the surgeon to visualize the position of the implant components three-dimensionally in the bone.

In this work, we demonstrate the clinical use of a virtual 3D planning system for hip joint replacement [6], which integrates patient-specific biomechanical properties of the affected bone and the available implants into the preoperative planning process (see Figure 1). The system allows the surgeon to select the optimal implant according to the prediction of individual load transfer from the implant to the bone. Advanced visualization techniques like volume rendering are used to provide the surgeon with a comprehensive and intuitive image of the bone anatomy as well as the three-dimensional stress distribution in the bone.

II. METHODS

The implant planning system is based on a finite element analysis to simulate loads in the proximal femur, which consists of cortical stiff tissue and trabecular spongy tissue. The simulation uses a patient-specific finite element model

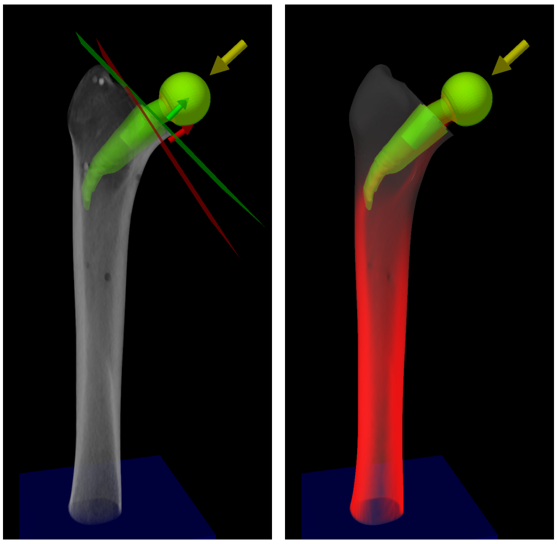


Fig. 1 Implant planning environment: Left: Semi-transparent rendering of the femur and the implant in combination with volume rendering of the femur's interior structures support the positioning of the implant. Right: The arrow on the sphere indicates the load on the femur, and the simulated stresses are visualized using volume rendering.

of the femur, which is generated from a high-resolution CT scan. In a preprocess, the femur is segmented from that CT scan, yielding a CT voxel model based on a 3D orthogonal hexahedral grid. For each voxel, material properties such as Young's modulus and Poisson's ratio are derived directly from the measured Hounsfield unit value [7, 8]. The physical model underlying our approach is based on linear elasticity and thus mimics the behavior of the bone at the macro-level during normal movements [9].

Due to an optimized multigrid solver, the system enables interactive load simulations using reasonably sized finite element models [10]. Furthermore, it can be used to simulate bone and implant loads on a standard desktop PC system at the full resolution of the CT scan, i.e., one hexahedral finite element per CT voxel, and at simulation times of less than one minute. For our test data set, we have a CT slice thickness of 1.0mm and a pixel size of 0.74mm. The resulting FE model consists of 520,000 hexahedral elements with more than 2 million degrees of freedom.

One possibility to simulate the interaction between the implant and the surrounding bone is to remove from the bone voxel model those voxels that would have been drilled away by the surgeon, and to simulate the interaction of the holed model with a separate model of the implant. As these operations cannot be performed at interactive rates for reasonably sized data sets, we have developed a different approach which is based on a voxelization of the implant with respect to the initial CT voxel grid. Voxels covered by the implant get assigned a stiffness value corresponding to the respective implant material. Therefore, instead of modeling the contact between the bone and the implant explicitly, our method simulates a non-slip boundary between both objects, with the resolution of this boundary being determined by the resolution of the voxel grid. The removal of the trabecular head region once the implant is inserted is simulated by masking the respective voxels.

Due to the stiffness of the bone, only the computed stress per hexahedral element is of relevance and the deformation of the femur can be neglected in the 3D visualization.

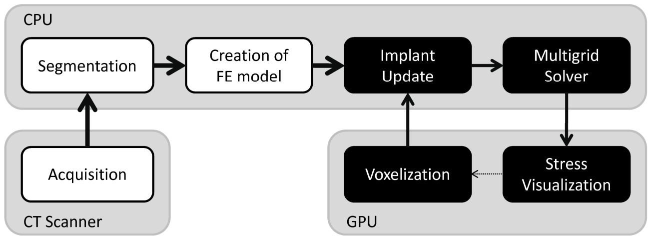
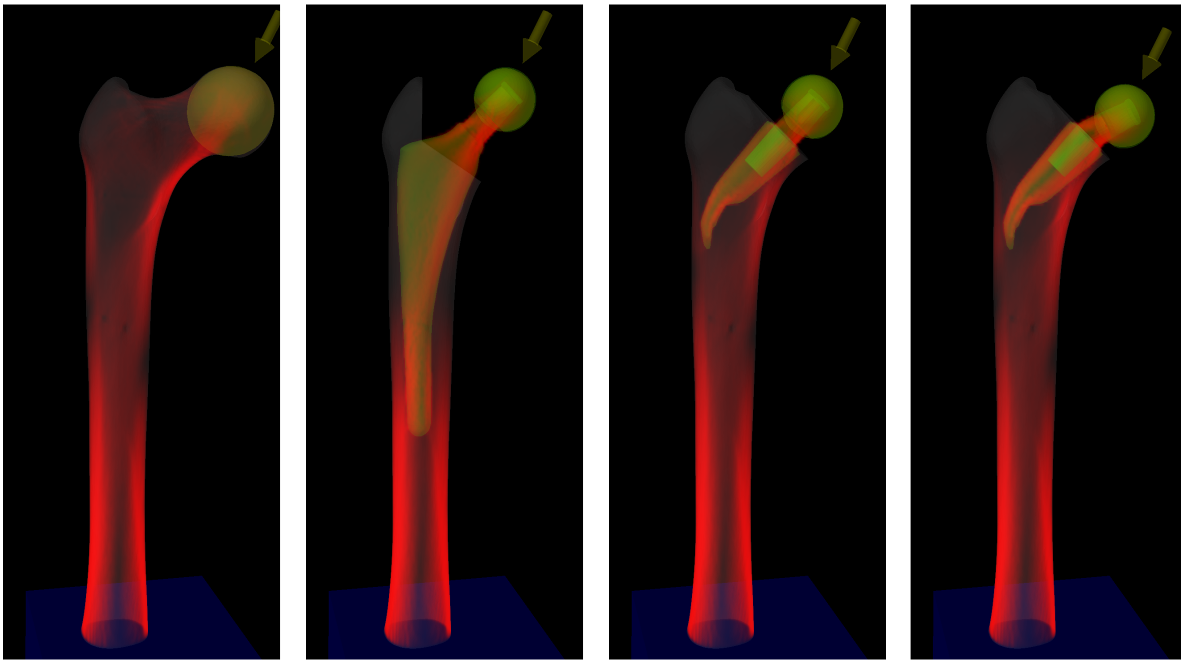


Fig. 2 Overview of the main components of the implant planning system.

Figure 2 gives an overview of the components of the implant planning system. The components colored white are preprocesses, which have to be run only once to build the patient-specific FE model. The other components are part of the interactive design loop. The loop starts with the voxelization of the implant according to its current shape and position, which is performed by utilizing the PC's graphics hardware (GPU) [11]. The resulting binary volume is transferred to the CPU, where it is used to update the material properties of the voxels covered by the implant, and thus to incorporate the implant into the FE model. After updating the simulation matrices, the FE simulation engine computes the stress distribution in the bone. The resulting stress scalar field is finally transferred to the GPU for visualization. These steps are repeated in the interactive design loop while the user changes the implant shape and position in the bone.

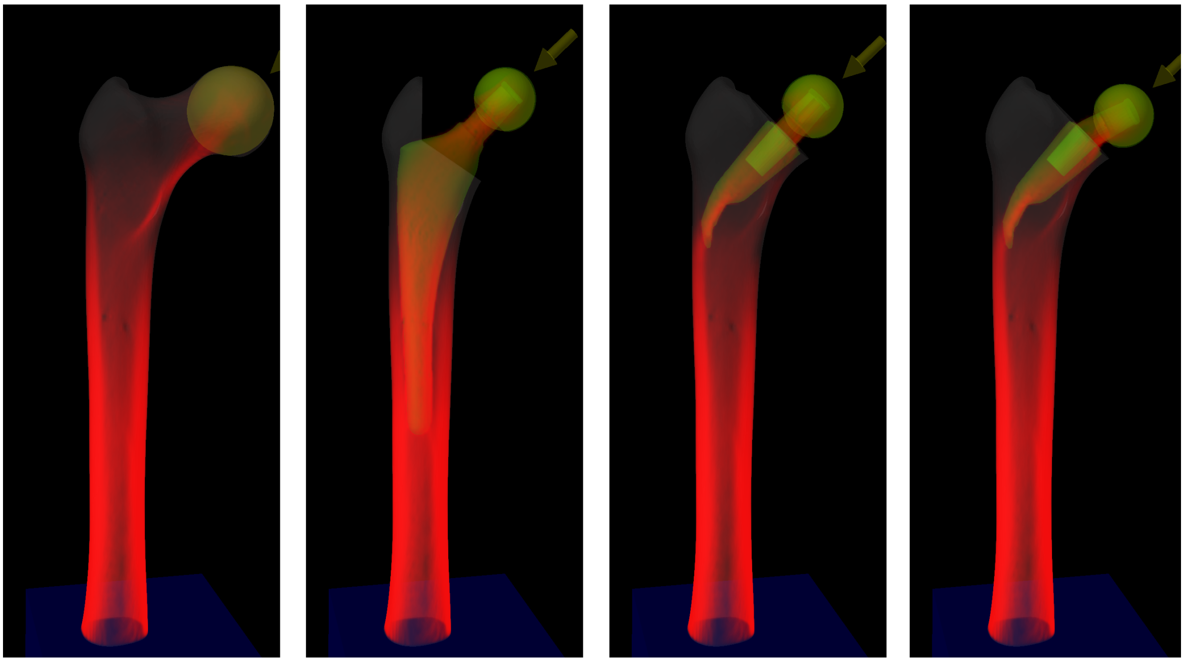
III. Results

In this section, we show simulation results, and demonstrate how our system helps to optimize the clinical procedure of hip-joint replacements. We present a series of implants that are inserted into a patient-specific model of the femur, which has been generated from a CT scan. All implants considered are from one manufacturer, ESKA Implants Lübeck. First, a classical G2 implant is used. Second, a modern CUT implant, which is much smaller in size, is inserted. Such bone-sparing implants are beneficial since they allow for potential revisions later on. Revisions might



Intact bone | G2 implant | CUT implant (straight conus) | CUT implant (angled conus)

Fig. 3 Visualization of the stress distribution in a femur for the intact bone and three different implants after removal of the femoral head. In all images the same load on the femur is simulated.



Intact bone | G2 implant | CUT implant (straight conus) | CUT implant (angled conus)

Fig. 4 Visualization of the stress distribution in a femur for the intact bone and three different implants after removal of the femoral head. In all images the same load on the femur was simulated. However, the direction of the force is modified by 20° in comparison with the load in Figure 3.

be necessary due to aseptic loosening, and they require inserting larger implants. Thus, starting with small implants improves the long-term prognosis of the patients. In the third example, the same implant is inserted with an angled conus, which provides the possibility to better reproduce the original position of the femoral head rotation center.

For all three implants, we simulate the same load on the femur. Figure 3 shows the resulting stress distributions and, for comparison, the simulated physiological stress distribution in the intact bone (the visualization is based on the von Mises norm of the stress tensor). It is clearly visible that the G2 implant yields stress shielding, as large parts of the femur have a significantly reduced load due to the transmission of load through the implant. For the second implant, it can be observed that the stress patterns are much closer to the physiological stress distribution, and the effect of stress shielding is not as high as in the first example. By ensuring that the implant matches the original position of the femoral head rotation center as good as possible (third implant), higher stress in the upper right cortical bone region can be observed. The resulting stress pattern matches the physiological distribution to a very high degree. The exact percental difference can be calculated.

Furthermore, for all three implants we simulate a slightly different load situation. The resulting stress distributions can be found in Figure 4. The implants are positioned in exactly the same way as in Figure 3. In direct comparison of both figures, one can observe a different overall stress situation. However, it still can be observed that implants from left to right match the physiological stress distribution better and better.

However, in real world the benefits of the modern implants are not yet fully evident. One possible reason is that it is more difficult to find the optimal implant size and position for a specific patient. Non-optimal placements or sizes can yield to reduced stress in the cortical region closely beneath the implant, which can potentially result in bone atrophy with the risk of aseptic loosening. Therefore, there is an increased need to support the surgeon in a preoperative planning process, especially for abnormal anatomies or revision cases. The introduced system allows for an effective preoperative planning due to the visualization options provided, and it has the potential to improve the long-term prognosis of the patients.

IV. Conclusion

We have presented a 3D simulation system for hip joint replacement planning. By efficiently simulating the load on the femur taking into account a selected implant's shape as well as its current position, the surgeon can receive a detailed visualization of the current stress distribution in a virtual planning environment. The implant design can be optimized based on the patient-specific data incorporated into the simulation process. Therefore, the system has a great potential to improve the long-term prognosis of patients, especially in the case of abnormal anatomies or revision cases.

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