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Comparison of Micromotion of Different Femoral Stems During Gait: A Quantitative CT-Based Finite Element Analysis

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Abstract. With the increasing availability of CT scans, it is now possible to use patient CT data for tailoring a patient-specific treatment method. The CT-based FEM software MECHANICAL FINDER was used to evaluate the values of micromotion of 4 different femoral stems in simulation of THA (total hip arthroplasty) with real CT patient femoral data and STL files of femoral implants. The analysis was done using literature-obtained muscle forces and boundary conditions of the human femur at an arbitrary gait cycle. As expected, it was found that the shortest stem exhibits the highest values of micromotion (L = 80 mm, total micromotion up to 39 μm) compared to a longer stem (L = 100 mm, total micromotion up to 28 μm). Even longer stems (L = 120 mm and L = 140 mm) show values ranging between the first two. This approach shows potential viability of using simulations to predict osseointegration in patient-specific conditions available for medical practitioners. Experimental verification is still necessary.

Introduction

Aseptic loosening of the acetabular and femoral component as a result of loss of primary stability is the main reason of early implant failure in THA patients. As a measure of osseointegration, micromotion monitoring is a viable tool that can determine the movement of the femoral component relative to the bone. While some small movement (generally above 40 μm) can be beneficial for bone ingrowth, displacements larger than 150 μm completely inhibit bone ingrowth [1]. Large micromotion is generally bad for osseointegration, especially in cemented implants where motion can lead to cracks and residue of methylmethacrylate [2]. Micromotion, just like osseointegration, is also directly linked with bone quality of the individual, which depends mainly on their diet, physical activity, age, sex and disease [3].

Objectives

The main goal of the research is to determine the influence of femoral stem length on the micromotion along different axes of motion. As excessive motion is undesirable, numerical methods, such as FEM can serve as a precursor to the design of novel implants or to analyze an individual patient's susceptibility to micromotion of the implant stem in the femur. Therefore, the presented method aims to provide a tool that medical practitioners can potentially use in practice to determine the optimal implant and/or optimal implant position for a specific patient based on calibrated CT data.

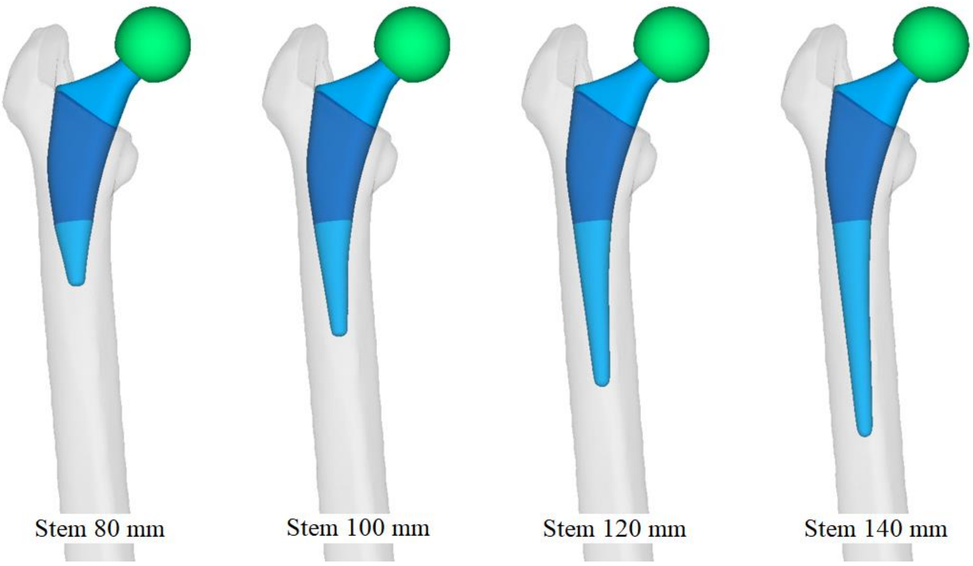

Fig. 1: The length, shape and placement of all analysed femoral stems

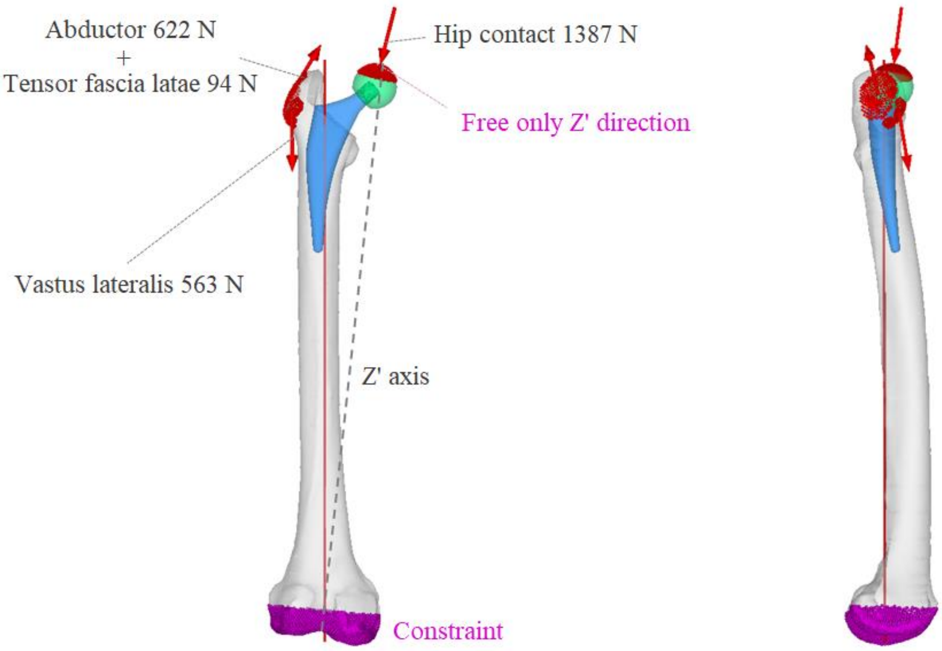

Fig. 2: The boundary conditions applied to the model of human femur. BW = 600 N. Derived from [4]

Study Design & Methods

The presented study focuses on FEM analyses of different variants of stems used in femoral implants with regard to micromotion between the implant and bone. Four geometrical solutions of the implant stem are presented. All implant variants have conventional straight stems and they vary in length (Fig. 1). The used software is MECHANICAL FINDER, a FEM-based practical tool utilizing patient-specific CT data to obtain a realistic, inhomogeneous material properties from calibrated CT scans. An anonymized CT scan, which is the subject of the research, has been calibrated by a phantom and served to create a 3D model of the femur. Real STL implant data have then been imported into the software to simulate a realistic post-operation environment. The global matrix of stiffness is then derived based on specified bone material model, which reads calibrated CT values (Fig. 3). Therefore, the software is able to create a fully inhomogeneous model of bone of individual patients. Boundary conditions are applied from each muscle forces and hip contact force in an arbitral cycle of gait (Fig. 2 [4]). The measure of osseointegration used in this study is stem micromotion relative to the human femur in the lateral-medial, posterior-anterior and proximal-distal axes.

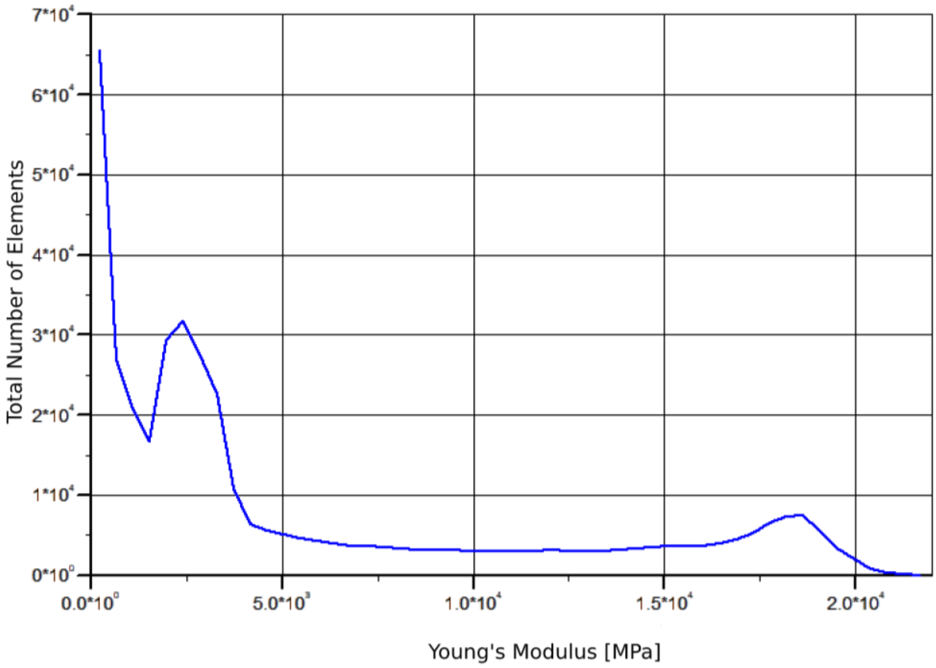

Fig. 3: The Young's Modulus histogram of the analyzed patient-specific CT scan

The FE mesh composed of linear (1st order) tetrahedral elements with element-unique values of Young's Modulus derived from the calibrated CT scan (Fig. 3). The number of elements for each analyzed variant, as well as the computation times, are shown in Table 1. The values of Young's Modulus were in the range of (minimum threshold) 0.001-21928 MPa. The minimum value is set so as to represent the softest materials in the bone while still maintaining some stiffness.

Table 1: Numbers of FE elements and length of computation for different stem variants

Stem variant	Number of elements	Length of computation [s]
L = 80 mm	502979	3510
L = 100 mm	517041	4577
L = 120 mm	526886	7471
L = 140 mm	543475	8936

Results

Micromotion between the stem and the femur was below 150 μm in stem types during gait, although their distribution was different, as shown in Fig. 3-6. The commonly recognized criterion for osseointegration (micromotion < 150 μm) was satisfied. The shortest stem (L = 80 mm) has shown the greatest values of micromotion (39 μm) and the least amount of micromotion was recorded for the second smallest (L = 100 mm) stem (28 μm). Variants L = 120 mm and L = 140 mm have shown values of 31 μm and 34 μm, respectively.

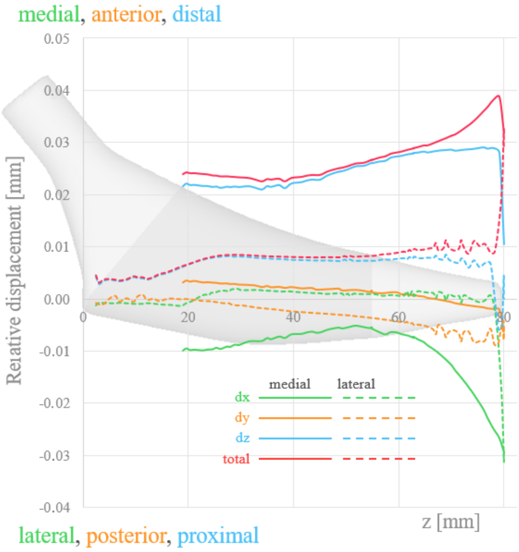

Fig. 4: The micromotion of the shortest (L = 80 mm) stem variant

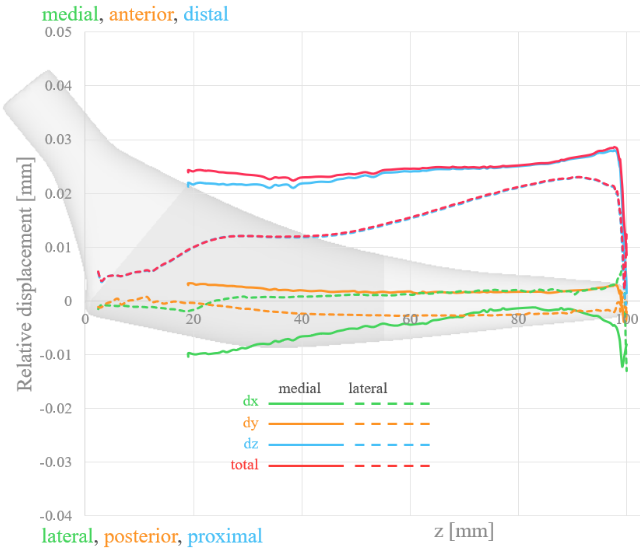

Fig. 5: The micromotion of the L = 100 mm stem variant

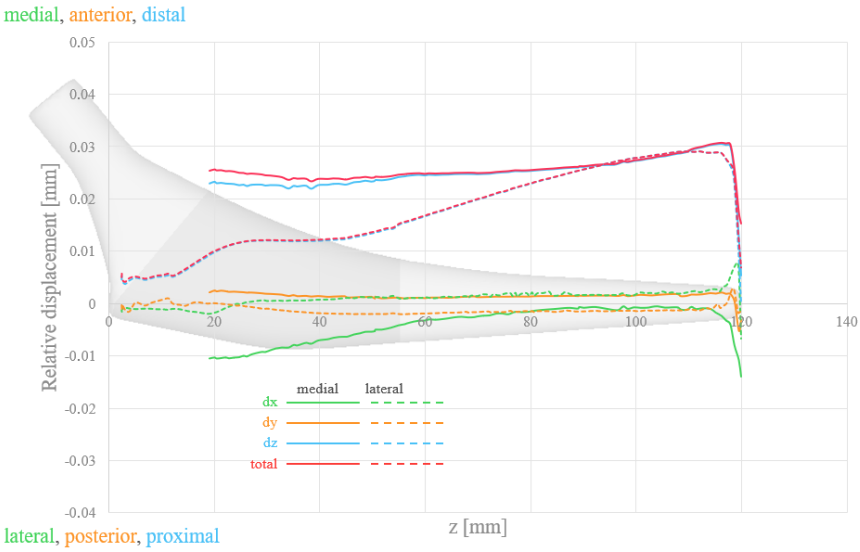

Fig. 6: The micromotion of the L = 120 mm stem variant

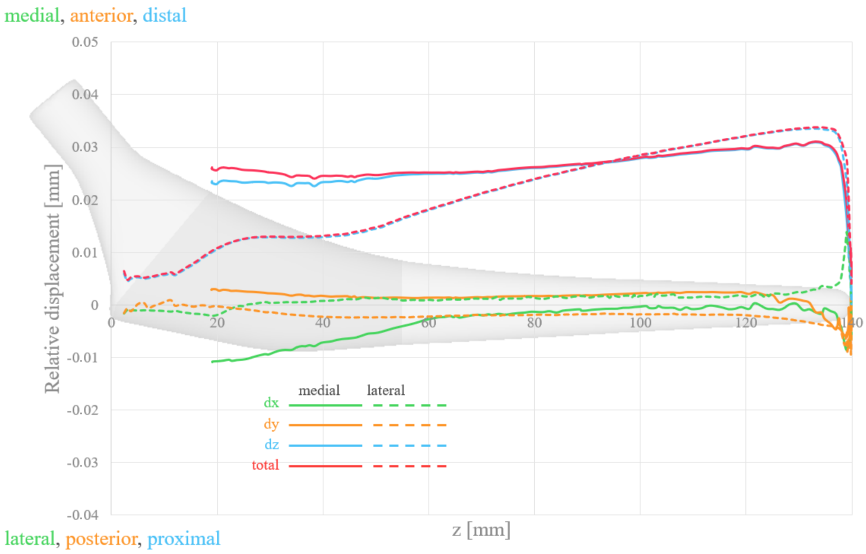

Fig. 7: The micromotion of the longest (L = 140 mm) stem variant

Conclusions

In this analysis, we only analyzed the gait cycle on four implants which differ in length. If the load does not exceed extreme values, micromotion is well within the tolerance required for bone osseointegration (< 150 μm) for all implant stem variants. The maximum values of micromotion seem to stabilize among the 3 longest implant variants (length above 80 mm). However, stress shielding might be more important when considering long-term bone atrophy in THA patients. As choosing the right implant (length and shape) for a patient poses the question of bone quality, a simulation showing the stress distributions of different implant variants for a specific CT scan of a patient might also be desirable.

Acknowledgment

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