Trabecular bone tissue strain distributions in the healthy and osteoporotic proximal human femur during a fall to the side

TRABECULAR BONE TISSUE STRAIN DISTRIBUTIONS IN THE HEALTHY AND OSTEOPOROTIC PROXIMAL HUMAN FEMUR DURING A FALL TO THE SIDE

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Introduction

The devastating effects of proximal femur fractures are felt particularly by the elderly. Due to osteoporosis bone strength decreases and, as a result, proximal femur fracture risk increases. Bone mineral density (BMD) and morphologic properties are commonly used predictors of proximal femur strength. Although loading of trabecular and cortical bone depends on such parameters, fracture is a mechanical phenomenon governed by exceeding tissue stresses and strains. Information about the local loading condition of the bone tissue could therefore lead to a better understanding of bone-fracture etiology.
Evaluation of tissue-level stresses and strains due to externally applied forces is possible with micro-finite element (µFE) analyses. In a previous study, we used this approach to determine tissue-level stresses and strains in a normal and an osteoporotic femur during physiological loading [1]. In this study we assessed tissue-level stresses and strains in the human proximal femur subject to a fall to the side. A particular purpose of this study was to determine the safety factors against permanent deformation and fracture for the healthy and osteoporotic proximal femur, based on local strains during a fall to the side.

Materials and Methods

Based on close-matched age, body weight and length, a healthy (T-score: -0.5, trochanter and neck BMD: 0.976 and 0.917 g/cm2, respectively) and an osteoporotic (T-score: -4.0, trochanter and neck BMD: 0.656 and 0.496 g/cm2, respectively) human proximal femur were selected for the creation of two large-scale µFE-models [1].
Boundary conditions were applied to simulate a fall to the side onto the greater trochanter, based on a typical experimental configuration [2-4]. An arbitrary hip force of 1000 N was distributed over the femoral head. The individual force vectors on the surface were directed towards the center of the head to simulate a frictionless cartilage layer. The force was distributed in such a way that the angle between the resultant hip force and the neck axis, and the angle between the shaft axis and the horizontal were equal to 15 and 10 degrees, respectively (Fig. 1). The nodes on the surface of the trochanter in a 0.5 cm thick layer perpendicular to the resultant hip force were fixed against vertical displacement. The distal end of the shaft was fixed in the horizontal direction.
Maximal (largest magnitude) principal strains were calculated in each element and filtered for increased accuracy [5]. The safety factor against permanent deformation was evaluated as the ratios between the filtered maximal principal-strain values in the cortex and the cortical-tissue tensile and compressive yield strains (0.73 % and 1.30 %, respectively [6]). The safety factor against fracture was determined with a global failure criterion [7]. The corresponding failure load was obtained by multiplying the resultant hip force with the predicted safety factor against fracture.

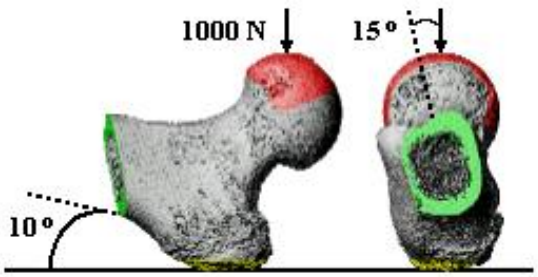

Fig. 1. Orientation of the proximal femur and resultant hip force during a fall to the side. The boundary conditions on the head, trochanter and distal end are represented by red, green and yellow areas, respectively. The dotted lines represent the shaft and neck axes.

Results

The tissue stresses and strains were higher in the osteoporotic femur than in the healthy femur (Fig. 2). The highest strains were found in the cortical tissue in the femoral neck.
Safety factors against permanent deformation of 6.4 and 4.5 were found for the healthy and osteoporotic femur, respectively. In both cases tensile yield was reached before compressive yield. The global failure criterion resulted in safety factors against fracture of 6.1 and 4.0 for the healthy and osteoporotic femur, respectively.

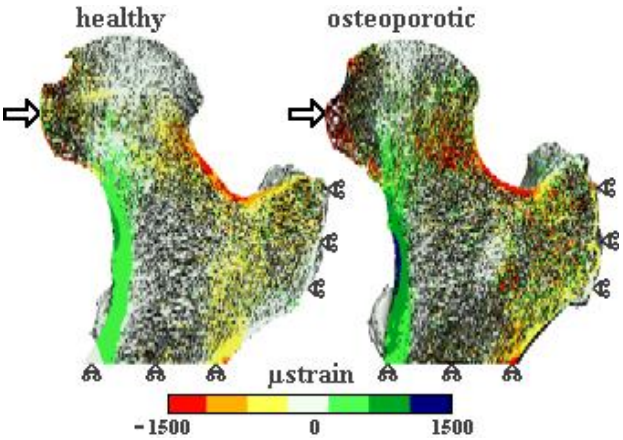

Fig. 2. Maximal principal strains in the healthy and osteoporotic proximal femur. The posterior halves of the micro-finite element models are shown.

Discussion

High maximal principal-strain values were found in the cortex of the femoral neck. Although completely different boundary conditions were used in this study compared to normal functional loading cases [1], the trabecular bone directs the forces to the same regions. Although osteoporosis mainly affects trabecular bone, it seems to have its effects on fracture risk indirectly, by increasing cortical strain values.
High tensile strains were found on the inferior side, in the cortex of the femoral neck, and high compressive strains on the opposite side. Although the absolute strain values in the superior region are higher, yield was predicted to start in the inferior region, due to the asymmetric strength of the tissue. This suggests that the loading conditions in a fall produce fractures starting in the inferior basicervical cortex, as also found experimentally [3].
The failure loads predicted (6.4 kN and 3.9 kN) compared well with values reported in literature, based on BMD values in femoral neck and trochanter [2-4]. However, the corresponding safety factors are lower than the predicted safety factors against permanent deformation. The adopted global failure criterion was developed for failure predictions for the distal radius [7] and could be inaccurate for other sites and loading conditions.

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References: [1] van Rietbergen et al., J Bone Min Res 18:1781-1788, 2003 [2] Courtney et al., Calcif Tissue Int 55:53-58, 1994 [3] Courtney et al., J Bone Joint Surg 77A:387-395, 1995 [4] Cheng, et al., Bone 20:213-218, 1997 [5] Charras and Guldberg, J Biomech 33:255-259, 2000 [6] Bayraktar et al., J Biomech 37:27-35, 2004 [7] Pistoia et al., Bone 30: 842-848, 2002.