Stress analysis of the proximal femur used in the assessment of AVN

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ABSTRACT INTRODUCTION: Current methods to assess the fracture risk for patients with bone diseases like avascular necrosis need improvement to help clinicians to find a suitable minimally invasive treatment. The strength of bones, including the femur, have been calculated using structural mechanics, bone is a structural member subjected to stress and strains. If the bone is being cut virtually, the normal and shear stresses in the cross section can be calculated, however, complex geometric aspects of the slicing direction may influence the stress calculation. The geometry of the femoral head, neck and trochanter region is also relatively complex in terms of loading. The bone is subjected not only to axial compression but also a significant bending moment. Moreover, it is subjected to forces and moments which vary in magnitude and direction for different loading situations like standing, gait and other activities. The aim of this study was to analyse the relevance and influence of loading as well as geometric and material parameters for the assessment of fracture risk of the proximal femur in a model simulating AVN lesions.

METHODS: A computational tool was created which predicted the stress and strain of the bone structure under loading and its susceptibility to geometric and material properties. Beam theory was used to calculate the maximum loading force at which the bone was likely to fracture by using a strain based failure criterion. A curved beam reflected the proximal part of the femur as the curvature of longitudinal axis in trochanter-neck region is relatively large. However, it did not reflect the subchondral area in the femoral head. Therefore, additionally to the curved beam which ran from the centre of the femoral head to the shaft, there was a straight beam which followed the simplified loading vector from the bone surface to the centre of the femoral head (Fig 1a). The forces acting on the upper femur were simplified and merged to a single static joint contact force pointing to the centre of the femoral head. Geometric and material properties such as Young’s modulus were derived from non-invasive three dimensional computed tomography images (QCT) using a material model. A single CT-scan of a ‘healthy’ femur was used in this study. Several manipulated CT-images were created which contained a simulated cone shaped lesion with reduced material properties. The lesions were included at four different positions within the femoral head while the volume and shape remained constant (Fig 1b). Those lesions were supposed to represent necrotic bone tissue with reduced stiffness. Therefore healthy, and bones with lesions were directly compared. Beside the lesion position, the loading vector was also altered in order analyse parametric effects. Two loading situations were used, namely neutral (vertical) flexion for stance and 20 degrees flexion for heel-strike. The developed tool calculated axial (EA) and bending rigidities (EI), the modulus weighted centroid, which is assumed to be the neutral axis, as well as torsion, normal and shear stress. Finally, the computational results were validated against a solid 3D-printed model of the respective CT-scan of the femur including a simulated AVN lesion. Rapid prototyping offers a good way to analyse the geometry of the bone as it is more consistent compared to real bone and the material properties are known. The model was compression tested and the results were compared with the predicted results from the tool.

RESULTS SECTION: The highest equivalent stress in each cross section of both beams was calculated and compared for different loading conditions and lesion positions. Although all simulated lesions were of the same volume, some of them resulted in higher stress concentrations in some areas and hence were potentially more severe. The simulated lesion with an angle of 10° had the highest influence followed by -25°, 80° and then 45°. The simulated heel strike resulted in higher stress in the femoral head area. It was up to 25% higher compared to stance loading. In the stem the stress was constantly 6% lower for all tested lesion cases. Axial and bending rigidities considered both material and geometric aspects of those cross sections. However, the influence of the bending rigidity on the structural integrity of the bone significantly depended on the loading vector. There was unsurprisingly a high bending moment in the shaft and parts of the femoral neck and one would assume a negligible bending influence on the femoral head. However, analysing the straight beam part, the bending influence varied from being greater than the axial compression to almost no influence at all. That means that rigidity was not a sufficient indicator for fracture risk on its own but must be seen within contexts of other parameters such as the loading vector and the material distribution inside the bone. This is particularly important for the development of a fracture prediction tool. The two main sites of fracture of the mechanically tested 3D-printed model correlated with the predicted results from the computational calculation. The first fracture occurred in the femoral head in proximity of the simulated lesion (Fig 1c). The lower end of the femoral neck fractured at a load which was 3.4 times higher with 12,600 N.

DISCUSSION: This study demonstrated that the lesion position and loading of the bone play an important role for analysing the fracture risk. When assessing the fracture risk not only the highest calculated stress or the rigidities but all relevant parameters should be considered as applying beam theory necessitates simplifications. The bone is sliced into cross sections perpendicular to the assumed beam axis. It is assumed that the stress is uniformly distributed over the cross section in accordance to the Saint-Venant’s principle. It is also assumed that the centroid is identical to the neutral axis. The compression test showed that a computational tool is capable of predicting accurate fracture sites within the bone. However, the magnitude of the fracture load was significantly lower than calculated which may be a result of the relatively high displacement rate of 2 mm/s. Further tests using a higher number of 3D-printed models should confirm these initial findings and results.

SIGNIFICANCE: This study will help to better understand failure mechanisms and mechanical behaviour of affected femoral heads which may also lead to an accessible non-invasive diagnostic tool which will assist the clinicians to find the most appropriate treatment in the clinical environment.

Figure 1: a) CT-image of a femoral head with assumed beam axis, planes of cross sections and loading force; b) Simulated AVN lesion positions within the femoral head; c) Fractured 3D-printed model including fracture lines after compression test;