INTRODUCTION
Measurement of bone mineral density (BMD) by DXA (dual-energy X-ray absorptiometry) is generally considered to be the clinical gold standard to diagnose osteoporosis. However, BMD alone is only a moderate predictor of fracture risk. Finite element analyses (FEA) of bone mechanics can contribute to a more accurate prediction of fracture risk (Cody et al. 1999). However, CT imaging is relatively expensive and inflicts larger radiation doses on the patient.

Methods to assess the 3D shape of the femur based on one radiograph and a shape template have been presented (Langton et al. 2009, Väänänen et al. 2010, Galibarov et al. 2010, Humbert et al. 2010). Only two of these studies were also able to estimate the internal architecture of the femur (Galibarov et al. 2010, Humbert et al. 2010). However, the accuracy of the internal architecture estimation was not evaluated in 3D. In addition, the effect of the estimation errors of 3D internal architecture on the outcome of mechanical analysis was not evaluated.

The aim of this study was to develop a method that is able to estimate both the 3D geometrical shape and internal architecture of the femur based on one 2D BMD image. The accuracy of the shape and internal architecture was determined, as well as the effect of these errors on the mechanical characteristics in FE analysis.

MATERIAL & METHODS
A method was developed to estimate the 3D geometrical shape and internal architecture of the proximal femur. The estimations were based on a 2D BMD image and a femur shape template. Proximal femurs of eighteen human cadavers were imaged with computed tomography (CT) (Siemens Definition AS64, voxel size 0.6 mm) and divided into two groups. The data from the first group (N = 9) were used to create a geometrical template based on 3D generalized Procrustes analysis (GPA) and thin plate splines (TPS). Subsequently, this template was applied to estimate the shape and internal architecture of the femurs in the second group (N = 9), based on a 2D BMD image projected from the CT images.

The geometrical errors in the shape between the original and estimated bones were evaluated in the whole proximal femur, and separately in the femoral head, neck, trochanter and shaft, based on volumetric error, which describes the difference in volume, and mean and maximum distance differences, which describe the distance between the surfaces of the original and estimated bones. The errors in the internal architecture were assessed similarly, by calculating the mean absolute errors between the original and estimated bone volumetric BMD (vBMD) values voxel-by-voxel.

Finally, FEA was conducted on the original and the estimated bone models using tetrahedral mesh (maximum element size 1.2 mm) and normal stance loading (Bergmann et al., 2001) to evaluate the effect of the geometrical and architectural errors on the mechanical strength. Stiffness, i.e., loading force divided by displacement at the loading nodes, maximum principal stress and von Mises stress were computed for both the estimated shape and the true bone shape (CT images) to evaluate the accuracy of the modelling.
RESULTS

Qualitatively, the shape of the proximal femur was estimated accurately (Figure 1). Most errors were located at the anterior and posterior sides of the femur. Moreover, the quantified errors in the geometrical parameters were small (Table 1). The volumetric difference between the estimated and original shape was 3.7% for the whole proximal femur. The head region was the most accurate followed by the neck, whereas the trochanter region was the least accurate (Table 1). The method was able to identify the main vBMD variation inside the femur (Figure 2). Absolute voxel-by-voxel BMD accuracy was moderate (Table 1), However, the errors decreased by 30% when the geometrical errors were removed.

Mechanical analysis revealed differences in stiffness of -7 ± 16 %, in mean principal of stress 5 ± 5 % and in von Mises of 5 ± 4 % between the FE models of original and estimated bones ($r^2=0.83-0.96$, p<0.01).

DISCUSSION

The fact that the geometrical errors were small indicates that the method is feasible for estimating the shape of the proximal femur. In the area of the head and neck, the mean distance difference was less than the size of one voxel. The mean distance difference of whole bone in our study was 0.88±0.19 mm, whereas other studies have reported significantly larger errors (Galibarov et al. 2010: 2.57-3.74 mm, Humbert et al. 2010: 1.3 mm). The accuracy of the estimation of femoral vBMD was moderate. However, over 30% of the errors were explained by the errors in shape estimation. The stiffness difference between the original and estimated bones was much smaller than that reported on our previous study (Väänänen et al. 2010).

The method for estimating the geometry and internal architectural structure of the proximal femur presented in this study gives better predictions of geometry, BMD distributions and mechanical characteristics than earlier ones. Hence, the proposed method is likely to lead to more accurate estimation of bone strength and ultimately fracture risk.

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REFERENCES