DXA-based Finite Element models for prediction of femoral strength: validation with experiments and comparison with aBMD and QCT-based Finite Element models

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Introduction

Femoral fractures cause excess morbidity, disability and mortality and are a major health problem which is likely to be aggravated by the aging of population. Areal bone mineral density (aBMD) measured with dual energy X-ray absorptiometry (DXA) is the gold standard clinical measure to evaluate fracture risk *in vivo*. 3D measurements can be performed with Quantitative Computed Tomography (QCT), but inducing higher radiation dose. DXA-based and QCT-based Finite Element (FE) analysis have been developed in recent years in order to improve the prediction of femoral strength. However, these models should be validated with accurate experiments *ex vivo* before a clinical application.

The aim of this study was to evaluate the ability of aBMD, DXA-based and QCT-based FE models in predicting the femoral strength in two loading conditions.

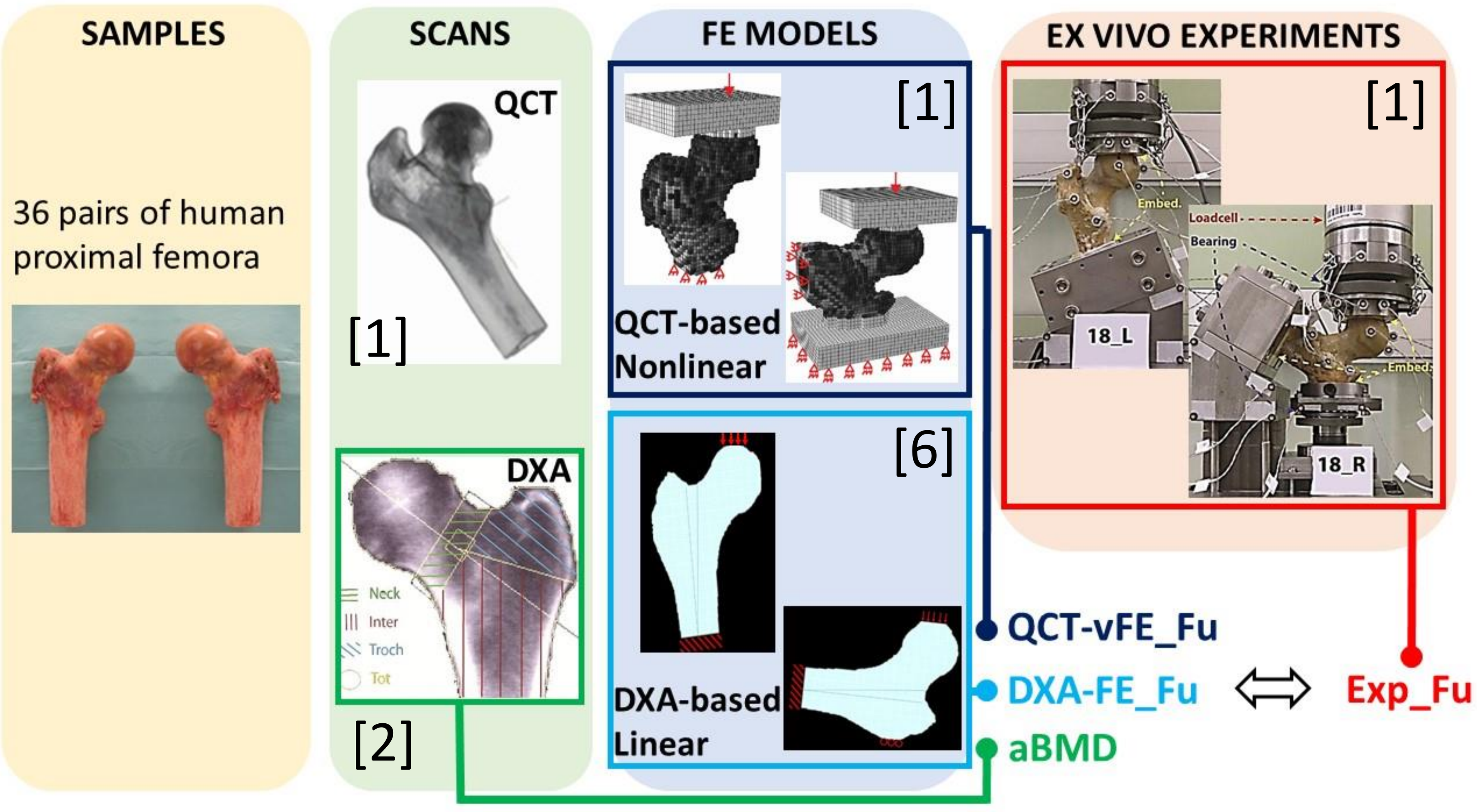

Figure 1: Overview of the methods applied to the 36 pairs of human femora.

Methods

Thirty-six pairs of **human femora** (17 males, 19 females with age 76±12 years, range 46–96) were dissected and scanned with DXA (pixel size 0.90x1.00mm²) and QCT (voxel size 0.33x0.33x1.00mm³)[1, 2]. aBMD and bone mineral content (BMC) were measured in different sites of the proximal femur (Total, Neck, Trochanteric and Intertrochanteric).

For each pair, one femur was **tested** in one-legged stance configuration (STANCE, 20° inclination from vertical plane) and the contralateral one in a backward sideways fall configuration (FALL, 30° inclination from horizontal plane, sample specific PU embedding on the greater trochanter in order to distribute the reaction force). The load was distributed on the superior (STANCE) or medial (FALL) side of the femoral head with specific PU embedding.

Heterogeneous isotropic nonlinear **QCT-based FE models** were generated for each sample. The 3D images were calibrated with densitometric phantom, resampled to 3mm in voxel size and converted into linear hexahedral elements. The nonlinear material properties were assigned based on BMD-BV/TV conversion and elastic-damage constitutive law [1].

Heterogeneous isotropic linear **DXA-based FE models** were generated from the aBMD distribution measured in each pixel of the 2D DXA image. The element size was 0.405x0.405mm². Each femur was assumed to be a plate with a patient-specific constant thickness t=3.5πW/16 (W is the mean femoral neck width). In each element aBMD was converted to BMD and then to Young's modulus, yield compressive and tensile stress by using experiment based relationships in the literature [3-5]. In each element the stress ratio was defined as the Von Mises stress and the average of tensile and compressive yield stress [6]. The femoral strength Fu was defined as the force that causes the stress ratio exceeding one, by dividing the peak force by the minimum stress ratio.

The **boundary conditions** in both model types reproduced the same loading configurations imposed in the experiments. For experiments and models, the femur failure loads were computed and compared.

Statistics: linear regressions analysis were performed for each predictor (aBMD, DXA-FE_Fu and QCT-vFE_Fu) of the measured experimental failure load (Exp_Fu). Multifactorial linear regression analysis was performed by including all densitometric and FE model outputs Significance was considered for α=0.05.

Results

Significant linear correlations were found between Exp_FU and all considered densitometric or FE model outputs (p<0.001 for all).

Among the densitometric predictors, neck aBMD was the best correlated with femoral failure load for both studied configurations.

If a multi-linear stepwise regression test was applied, by including Age, all densitometric variables, and both model predictions the only factors that improved the predictions were **QCT-vFE_Fu and DXA-FE_Fu for STANCE**, and **QCT-vFE_Fu and DXA-Neck_aBMD for FALL**.

In particular, for the FALL configuration the best predictors of bone strength was the QCT-based FE (R^2=0.85), followed by femoral neck aBMD (R^2=0.80) and DXA-based FE (R^2=0.76). For the STANCE configuration the best predictor was QCT-based FE (R^2=0.80) which was similar to the DXA-based FE (R^2=0.79), both were better than the femoral neck aBMD (R^2=0.66).

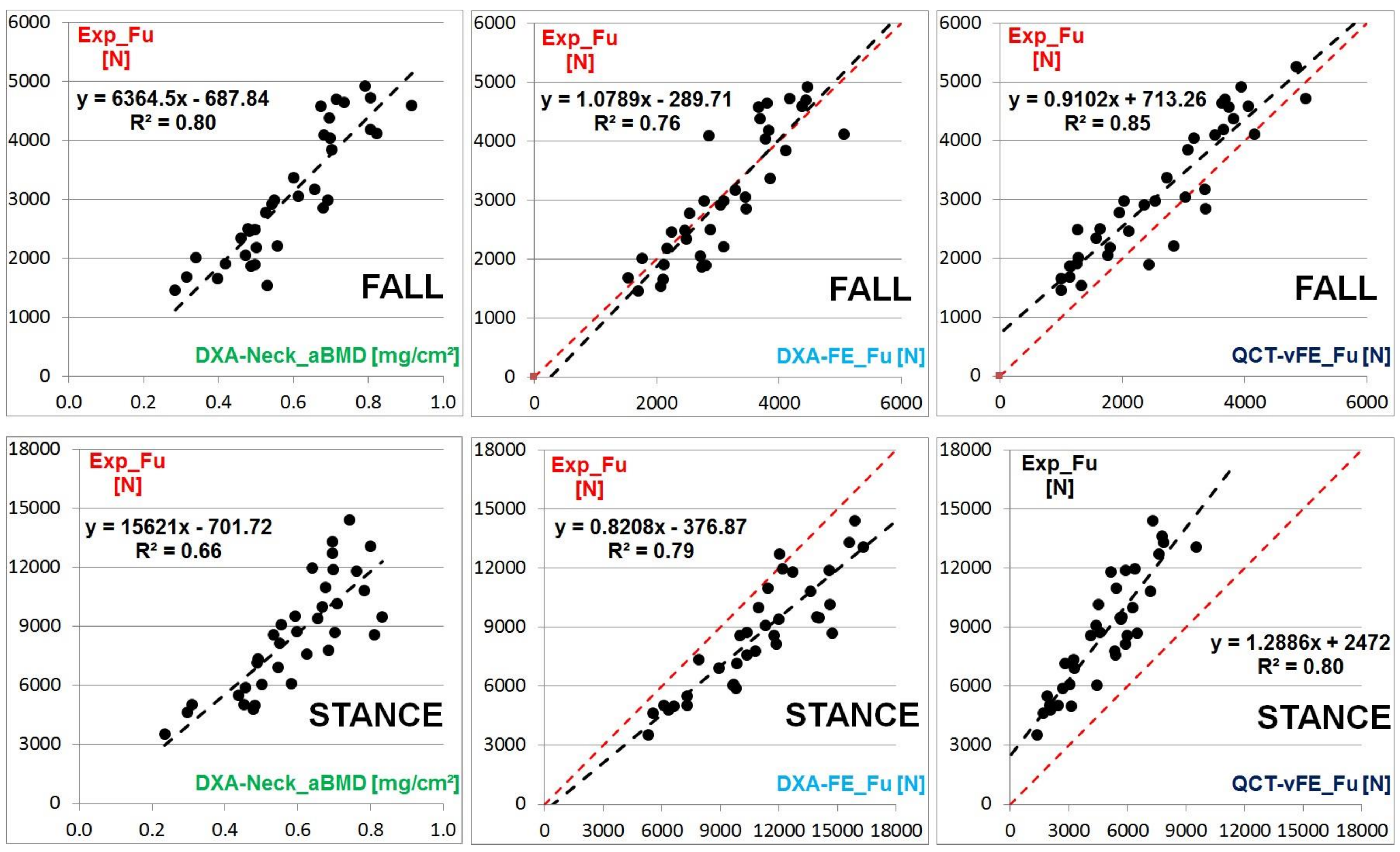

Figure 2: Prediction of femoral failure load Fu for FALL configuration (top) and STANCE configuration (bottom) with the standard aBMD (left, DXA-based FE models (middle) and QCT based FE models (right)

Conclusion

While QCT-based FE models have been found to be superior to both aBMD and DXA-based FE models in both configurations, the DXA-based FE models have shown good improvement for the STANCE configuration compared to femoral neck aBMD. Considering the clinical applicability of such models, future work needs to clarify if DXA-FE_Fu could improve the prediction of risk of fracture in clinical studies.

Acknowledgements

This study was partially supported by the FP7 European program (MAMBO: PIEF-GA-2012-327357). The authors thank Prof Kainberger for the access to the DXA.

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Disclosure

Authors have no conflict of interest

The Insigneo Institute for *in silico* Medicine is a collaborative initiative between the University of Sheffield and Sheffield Teaching Hospitals NHS Foundation Trust.

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