DXA-derived Finite Element models to enhance the hip fracture risk prediction

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Abstract—**Osteoporosis represents a major social concern due to progressive greying of the population. At present, the diagnosis is based on DXA-based T-score measurements, but the identification of subjects at higher risk of fracture still remains problematic. In this context, this work aims to explore the role of DXA based Finite Element (FE) models, in combination with T-score, in enhancing the risk of fracture prediction. 2D FE models were thus built and compared with previously developed CT-based FE models. Results support the promising role of DXA-based FE models, which could be generated using already available clinical data, in integrating the present diagnostic procedure.**

Keywords—**osteoporosis, fracture risk, Finite Element analysis, DXA**

I. INTRODUCTION

OSTEOPOROTIC fracture is a consequence of osteoporosis, a condition in which the loss of bone mass and the bone tissue degradation significantly compromise the bone strength. To date, osteoporosis diagnosis is based on T-score estimate, obtained from the DXA-based bone mineral density (BMD) measurement. However, the overlapping of cortical and trabecular bone on the image plane generated by the DXA projective nature [1] compromises its sensitivity in correctly identify the risk of fracture in individual patients [2] due to the loss of geometric and architectural related information [3]. Three-dimensional FE models have been shown to provide accurate fracture onset prediction [4] thanks to the large number of information they integrate (three dimensional subject specific geometry and three dimensional distribution inhomogeneous mechanical properties). Nevertheless, CT scans do not represent the first choice exam to diagnose osteoporosis due to the associated X-ray exposure and costs. On account of this, in the last few years the focus has shifted to 2D FE models developed starting from DXA images [5], the results of which have shown to enhance the estimate of the risk of fracture on the basis of information independent from BMD. Thanks to the availability of DXA and CT images for the same patients, this work aims to get further insights in the role of 2D FE models by comparing risk of fracture predictions deduced from CT-derived 3D FE simulations and DXA-derived 2D FE simulations.

II. MATERIALS AND METHODS

A. Data-set

This study is based on a data-set of 28 post-menopausal female subjects (55 to 81 years) treated in San Luigi Gonzaga Hospital in Orbassano (Italy). Both DXA images (Discovery DXA system, Hologic) and CT scans were available for the entire cohort. 3D FE model were built from CT data in a previous work [6]. Due to the absence of follow-up information for the 28 patients, two further patients who had undergone fracture were included, although the corresponding 3D model was not built due to the unavailability of the CT scans.

B. Local BMD definition

DXA scans of the proximal femurs were segmented and local BMD values were assigned hypothesizing a linear relationship between pixels grey intensity and BMD. In detail, two points were considered to extract the line slope: (1) the mean grey value obtained by averaging the non-zero pixels in the segmented region and corresponding to the average BMD provided by the Hologic software; (2) the line intercept, determined as the 20% of the average BMD, and intended as the minimum BMD value.

C. Finite Element analyses

Two-dimensional mesh of each segmented proximal femur was built adopting plane stress elements (size 0.5 mm) and assuming a constant thickness [7]. Using the previously defines local BMD map and the patient-specific thickness, BMD values were first converted in apparent density (ρ_{app}) [7], then, the empirical relations developed by Morgan and colleagues [8] were used to derive local Young's moduli (E):

$$E(MPa) = \begin{cases} 15010\rho_{app}^{2.18} & if\ \rho_{app} \leq 0.28\ g/cm^3 \\ 6850\rho_{app}^{1.49} & if\ \rho_{app} > 0.28\ g/cm^3 \end{cases} \quad (1)$$

Coherently with our previous study [6], a sideways fall condition was reproduced, accounting for subject-specific height and weight. For fracture prediction, a principal strains based criterium was adopted [9] to identify the maximum risk of fracture (RF) value, addressed as $\widehat{RF}$ in the following. In detail, at each element centroid the prevailing principal strain was divided by the respective threshold value [10] to obtain local RF. $\widehat{RF}$ close to or exceeding 1 were considered as fracture prognostic. In order to evaluate the predictive power of the 2D FE models with respect to the more exhaustive 3D model, correlations between the average Young's moduli and the $\widehat{RF}$ values were computed. Ultimately, comparisons between the computed $\widehat{RF}$ and the measured T-score was carried out to deepen the synergistic contribution of the two parameters in predicting a risk of fractures.

III. RESULTS AND DISCUSSION

Patient-specific Young's moduli averaged on the whole 2D model resulted significantly correlated (p<0.05) with CT-derived moduli. The hypothesized linear relation linking grey values and BMD led to a significant correlation between 2D and 3D $\widehat{RF}$ (Spearman's $\rho = 0.66$, $p < 0.001$). Figure 1 shows the comparison between the risk of fracture as predicted through the gold standard T-score and through the $\widehat{RF}$ coming from the 2D Finite Element analyses (Spearman's $\rho = 0.69$, $p < 0.001$). The T-score standard ranges, here shown in absolute value for the sake of simplicity, are: |T-score| < 1 normal, 1 < |T-score| < 2.5 osteopenic, |T-score| > 2.5 osteoporotic. As visible, patients with a non-pathological T-score are all gathered in the low risk region for the $\widehat{RF}$. Among osteopenic patients, some individuals appears at higher risk of rupture, although some others do not seem to differ from the average of healthy patients. The majority of patients classified as osteoporotic are located in the high risk region for the $\widehat{RF}$, but three individuals appears not at risk for the $\widehat{RF}$, including one of the two fractured patients. The reason lies in this patient's extremely low BMI (equal to 16), on which the boundary conditions applied to the model are based.
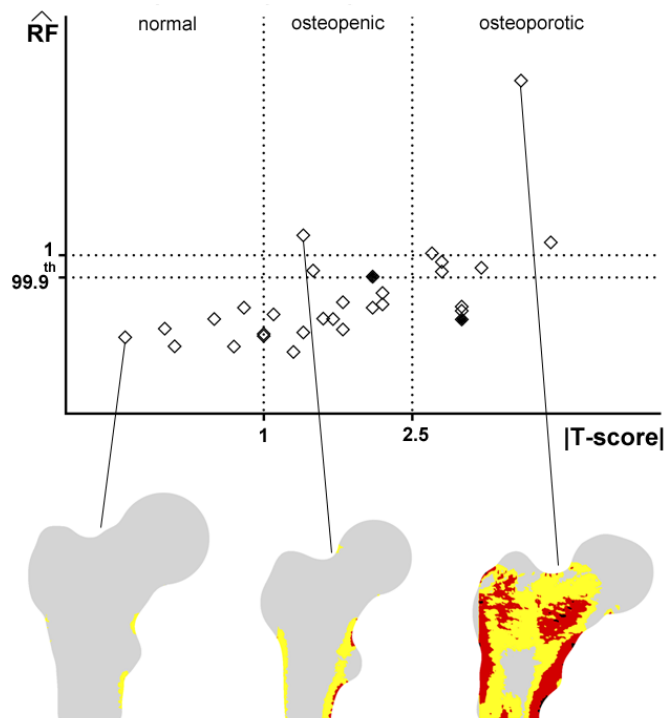
Figure 1. Comparison between |T-score| and $\widehat{RF}$. Filled diamonds refer to the two fractured patients. Not only $\widehat{RF}$ values exceeding 1, but also those exceeding the 99.9th percentile have been regarded as fracture prognostic. Contour maps of representative patients' *RF* classified as normal, osteopenic or osteoporotic by the T-score are shown in the bottom.

Moreover, a further and important factor is closely related to the femur geometries. Comparing patients with similar $\widehat{RF}$ but different T-score (Fig. 2a), they do not show significant geometric differences. However, comparing two profiles classified as osteopenic but with different $\widehat{RF}$ (Fig. 2b), they noticeably differ, highlighting the synergic effect of geometry and BMD in determining overall bone strength.
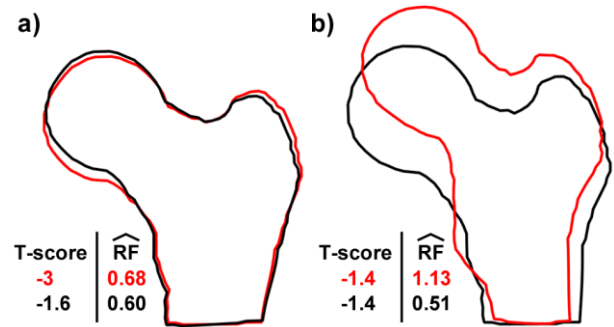
Figure 2. Comparison between shapes related to patients with a) comparable $\widehat{RF}$ but different T-score and b) viceversa.

IV. CONCLUSION

DXA-derived Finite Element models have demonstrated both a good agreement with CT-derived ones and a strong discriminatory ability among normal, osteopenic and osteoporotic individuals. The current clinical availability of DXA images makes the method developed in this study clinically applicable, in combination with the T-score, with the potentiality of enhancing the current gold-standard.

REFERENCES

[1] P. D'Amelio, C. Bignardi, M. Delise, P. Rossi, N. Lollino, *et al.*, "Bone Mineral Density and Singh Index Predict Bone Mechanical Properties of Human Femur," *Connect. Tissue Res.*, vol. 49, no. 2, pp. 99–104, 2008.

[2] J. A. Kanis, C. Cooper, R. Rizzoli, and J. Y. Reginster, "European guidance for the diagnosis and management of osteoporosis in postmenopausal women," *Osteoporos. Int.*, vol. 30, no. 1, pp. 3–44, 2019.

[3] S. P. Väänänen, L. Grassi, G. Flivik, J. S. Jurvelin, and H. Isaksson, "Generation of 3D shape, density, cortical thickness and finite element mesh of proximal femur from a DXA image," *Med. Image Anal.*, vol. 24, no. 1, pp. 125–134, 2015.

[4] P. Bhattacharya, Z. Altai, M. Qasim, and M. Viceconti, "A multiscale model to predict current absolute risk of femoral fracture in a postmenopausal population," *Biomechanics and Modeling in Mechanobiology*, Springer Berlin Heidelberg, pp. 1–18, 2018.

[5] Y. Luo, S. Ahmed, and W. D. Leslie, "Automation of a DXA-based finite element tool for clinical assessment of hip fracture risk," *Comput. Methods Programs Biomed.*, vol. 155, pp. 75–83, 2018.

[6] A. Aldieri, M. Terzini, G. Osella, A. M. Priola, A. Veltri, *et al.*, "Osteoporotic Hip Fracture Prediction: Is T-Score-Based Criterion Enough? A Hip Structural Analysis-Based Model," *J. Biomech. Eng.*, vol. 140, no. 11, p. 111004, 2018.

[7] K. E. Naylor, E. V. McCloskey, R. Eastell, and L. Yang, "Use of DXA-based finite element analysis of the proximal femur in a longitudinal study of hip fracture," *J. Bone Miner. Res.*, vol. 28, no. 5, pp. 1014–1021, 2013.

[8] E. F. Morgan, H. H. Bayraktar, and T. M. Keaveny, "Trabecular bone modulus-density relationships depend on anatomic site," *J. Biomech.*, vol. 36, no. 7, pp. 897–904, 2003.

[9] E. Schileo, F. Taddei, L. Cristofolini, and M. Viceconti, "Subject-specific finite element models implementing a maximum principal strain criterion are able to estimate failure risk and fracture location on human femurs tested in vitro," *J. Biomech.*, vol. 41, no. 2, pp. 356–367, 2008.

[10] H. H. Bayraktar, E. F. Morgan, G. L. Niebur, G. E. Morris, E. K. Wong, *et al.*, "Comparison of the elastic and yield properties of human femoral trabecular and cortical bone tissue," *J. Biomech.*, vol. 37, no. 1, pp. 27–35, 2004.