Hip fracture risk prediction through FE analysis: influence of HSA parameters

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***Abstract*—The current clinical gold standard for osteoporosis diagnosis is the measure of the areal bone mineral density (aBMD). However, 50% of fractures occur in individuals not classified as osteoporotic, demonstrating aBMD alone cannot predict fracture risk accurately. Aim of the study was to assess the geometrical parameters significantly affecting hip fracture risk probability. Twenty-eight subject-specific finite element analyses have been performed to simulate walking and falling, and the influence of the parameters on principal strains determined. The interaction of aBMD with buckling ratio and cross sectional area turned out to significantly affect strains in the sideways fall configuration, while the interaction between aBMD and body mass index was significant in the walk loading configuration.**

***Keywords*—Osteoporosis, hip fracture risk, HSA, finite element analysis.**

I. Introduction

OSTEOPOROSIS, caused by an imbalance in bone metabolism, results in the deterioration of bone microarchitecture, quality and consequently of bone strength, which markedly increases the probability of fracture. From this perspective, hip fracture is considered to be the most serious complication of osteoporosis, representing a major source of morbidity and mortality around the world [1].

The current gold standard for osteoporosis diagnosis and clinical fracture risk assessment is the use of dual energy X-ray absorptiometry (DXA), which measures areal bone mineral density (aBMD). However, the great limitation of aBMD is that it provides an estimate of the bone density projected on a two-dimensional surface, ignoring factors which do affect bone strength, such as bone geometry and spatial density distribution.

During the two last decades many efforts have been dedicated to the assessment of a more reliable prediction tool for hip fracture risk. Many studies adopted the hip structural analysis (HSA) method, which provides geometrical information from DXA data [2], [3], [4], trying to correlate geometry and fracture risk. In addition, finite element (FE) analyses have been extensively used due to the possibility to develop CT based subject-specific models able to account for the individual features in terms of geometry and material properties distribution.

In this work subject-specific FE simulations have been performed aiming to assess the HSA derived geometrical factors significantly affecting the strains experienced by the proximal femur. The identification of associations between subject-specific FE analyses and clinically available information would indeed strongly affect the noninvasive assessment of hip fracture risk.

II. Materials and Methods

Twenty-eight post-menopausal female subjects, aged from 55 to 81 years, have been engaged in the study after signing an informed consent. Clinical data including age, height, weight, BMI, BMD, T-score and HSA variables have been provided, together with CT scans of their right proximal femur.

A. FE Models

The CT scans were first imported in Mimics (v17, Materialise, Leuven, Belgium) where, after the segmentation, three-dimensional subject-specific models were created. Subsequently, using the 3-matic module in Mimics, the models were meshed using 4-node tetrahedral elements (Tet4). After the meshing procedure was completed, isotropic and inhomogeneous material properties were assigned (Fig. 1). Specifically, mathematical relations between density and the CT images Hounsfield Units (HU) [5] and between density and Young's modulus [6] have been set. A constant Poisson's ratio ($\nu = 0.3$) was assigned to the model. Since for the material properties assignment Mimics requires elements to be grouped in a discrete number of bins according to their density, a sensitivity analysis was performed in order to set the adequate number of bins. A look-up file was then written for the inhomogeneous material properties assignment, and 25 bins were considered.

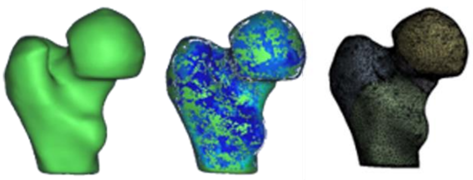

Figure 1: from left to right the 3-d model, the inhomogeneous material distribution, the meshed model.

B. FE Analyses

The 28 meshed models output from Mimics were imported in Ansys Workbench (v14.5, Canonsburg, Pennsylvania, U.S.), where 3-Matic Tet4 elements were converted to SOLID185.

Walk and sideways fall conditions were simulated, with subject-specific loads applied. To simulate the walk condition, approximated to a single-leg stance [7], the articular reaction force was applied on the femoral head, and the muscle force was assigned as a distributed force (15 mm radius circular area) on the greater trochanter. The sideways fall was reproduced constraining the femoral head surface and applying a distributed (16 mm radius circular area) compressive force on the side of greater trochanter [1], [4].

In both conditions, the femoral diaphysis was completely fixed 5 mm distally from the lesser trochanter. In order to analyse the variables significantly affecting hip fracture risk, neck and intertrochanteric regions have been considered separately. According to clinical observations indeed, hip fractures most recurrently occur at these anatomical locations [1]. Principal strains have been considered, since strains have been proved to dominate the fracture process [1] and growing consensus has been established on the adoption of maximum principal strain-based failure criteria [8]. In particular, since failure is thought to occur if tensile or compressive principal strains exceed limit values, the extreme strain values per each patient have been considered.

C. *Statistical analysis*

A two-way ANOVA coupled with a post-hoc test was carried out in the Matlab environment, aiming to assess which HSA variables most significantly affect strains at the two examined anatomical regions. Variables to be included had been identified as statistically significant by means of a preliminary one-way ANOVA.

III. Results and Discussion

Only the minimum principal strains (Fig. 2) were considered in the fall configuration, since during sideways falls the femur mainly experiences compressive strains. The average strain was -0.036 at the neck and -0.161 at the intertrochanteric site, both exceeding the compressive limit [8]. The minimum principal strains identified were -0.084 at the neck and -1.864 at the intertrochanter.

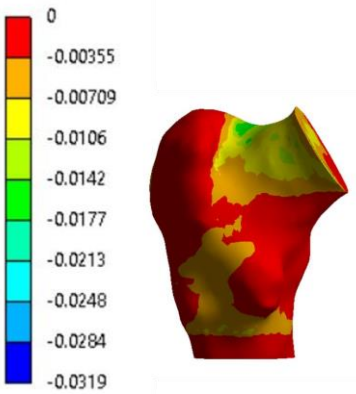

Figure 2: minimum principal strain distribution (mm/mm) experienced by one patient during the sideways fall configuration.

During the walking configuration instead, both minimum and maximum principal strains (Fig. 3) were analyzed. On average, minimum compressive principal strains set to -0.005 and -0.026, while the average maximum tensile principal strain set to 0.003 and 0.027 at the neck and intertrochanter respectively. Considering the extreme values of the whole patients set, the greatest compressive principal strains were -0.009 at the neck and -0.258 at the intertrochanter, while the highest tensile principal strains reached 0.006 at the neck and 0.195 at the intertrochanteric site. These results suggest that, during walking, the intertrochanteric site may be at higher risk.

The post-hoc test allowed to claim that, during the sideways fall, patients characterized by a low BMD coupled with a low cross-sectional area turned out to experience significantly ($p=0.015$) greater compressive strains at the neck, and those with a low BMD and a high buckling ratio at both the intertrochanteric ($p=0.04$) and neck ($p=0.001$) sites.

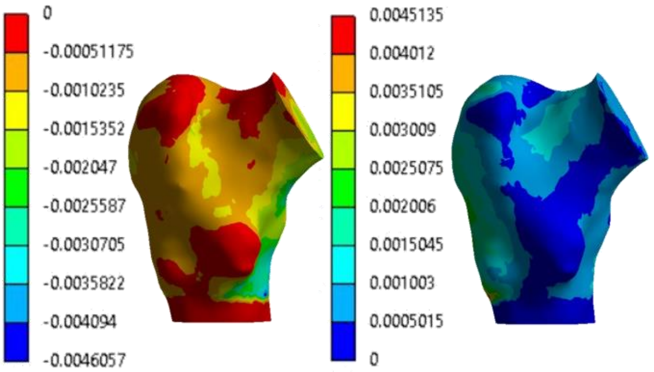

Figure 3: minimum principal (left) and maximum principal (right) strain distribution (mm/mm) experienced by one patient during walking configuration.

In the walk loading configuration, patients with a low BMD and a high body mass index experienced significantly higher compressive principal strain ($p=0.01$) and tensile principal strains ($p=0.04$) in the neck, while higher tensile principal strains were observed in the intertrochanter ($p=0.026$).

The results obtained are in good agreement with other studies concerning the significant influence of cross sectional area, buckling ratio [2], [3] and body mass index [4], [9]. Nevertheless, this study did not identify as statistically significant the hip axis length and the neck shaft angle, which have been considered significant predictors of hip fracture risk [2], [9]. The preliminary results here described will be widen in the next future with additional patients and will be validated through the introduction of the potential hip fracture history of the analysed patients.

References

[1] H. Kheirollahi,, Y. Luo, "Identification of High Stress and Strain Regions in Proximal Femur during Single-Leg Stance and Sideways Fall Using QCT-Based Finite Element Model," *World Academy of Science, Engineering and Technology, International Journal of Medical, Health, Biomedical, Bioengineering and Pharmaceutical Engineering*, 2015, vol. 9.8, pp. 633-640.

[2] M. Ito, et al. "Analysis of hip geometry by clinical CT for the assessment of hip fracture risk in elderly Japanese women," *Bone*, 2010, vol. 46.2, pp. 453-457.

[3] S. Kaptoge, et al., "Prediction of incident hip fracture risk by femur geometry variables measured by hip structural analysis in the study of osteoporotic fractures," *Journal of Bone and Mineral Research*, 2008, vol. 23.12, pp. 1892-1904.

[4] Z. Ferdous, and Y. Luo, "Study of hip fracture risk by DXA-based patient-specific finite element model," *Bio-medical materials and engineering*, 2015, vol. 25.2, pp. 213-220.

[5] J. Y. Rho, M. C. Hobatho, R. B. Ashman, "Relations of mechanical properties to density and CT numbers in human bone," *Medical engineering & physics*, 1995, vol. 17.5, pp. 347-355.

[6] E. F Morgan, H. H. Bayraktar, T. M. Keaveny, "Trabecular bone modulus–density relationships depend on anatomic site," *Journal of biomechanics*, 2003, vol. 36.7, pp. 897-904.

[7] J. Y. Kwon, et al., "Osteocyte Apoptosis-Induced Bone Resorption in Mechanical Remodeling Simulation-Computational Model for Trabecular Bone Structure," in: *Apoptosis and Medicine*. InTech, 2012.

[8] E. Schileo, et al., "To what extent can linear finite element models of human femora predict failure under stance and fall loading configurations?," *Journal of biomechanics*, 2014, vol. 47.14, pp. 3531-3538.

[9] S. Gnudi, E. Sitta, E. Pignotti, "Prediction of incident hip fracture by femoral neck bone mineral density and neck–shaft angle: a 5-year longitudinal study in post-menopausal females," *The British journal of radiology*, 2014.

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