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Proximal Femur Geometry as Moderator Factor for the Effect of Mechanical Loading during Gait – A Bone Remodeling Analysis

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INTRODUCTION

Hip fracture is an important public health problem that contributes to both morbidity and mortality in the elderly. Demographic changes in the coming decades will lead to huge increase in elderly population with more elderly living in countries with higher incidence rates of hip fracture (1). Despite suggestions that hip geometry influences hip fracture no consensus has been achieved about what and how geometric parameters can improve the prediction of the risk of hip fracture (2). Thus, the analysis of the spatial distribution of bone mineral density (BMD) related to the hip geometry may contributes for understanding the risk of hip fracture, specially because it has been shown that distribution of BMD at the proximal femur is related with the risk of hip fracture (3). Therefore, the purpose of this study was to map, by means of three-dimensional finite element method and a suitable bone remodeling model, the distribution of BMD at the proximal femur associated with geometrical features, namely with the femoral neck length-FNL, the femoral neck width-FNW and the neck shaft angle-NSA.

METHODS

Development of a parameterized finite element model (FEM)

A reference left proximal femur geometry (4) was discretized using tetrahedral elements (Abaqus FEA®, element type C3D4), given rise to a refined finite element mesh. The geometric parameters of the reference femur were defined according to Mahaisavariya et al. (5) (Table 1). A parameterized 3-D FEM of the reference mesh (Figure 1) was incrementally adjusted to adopt physiological ranges at the FNL, FNW and NSA (6), yielding a set of femur meshes with different geometries (Table 2).

Bone remodeling model

A validated bone remodeling model based on structural optimization techniques was used to obtain the BMD distribution for each femur (7). In this model, bone tissue was formulated as a porous, orthotropic, oriented and linear elastic material, with Young's Modulus of 20 Gpa and Poisson coefficient of 0.3 (base material). This remodeling model assumes a self-adaptation of bone to achieve the stiffest structure according to the mechanical loading to which it is submitted. For this end it was considered a single load condition comprising hip contact force (HCF) and hip muscle forces of the abductor, vastus lateralis and medialis muscles of the instant of maximum HCF in the gait cycle of a reference subject (Figure 2) (8).

Mapping the distribution of bone mineral density (BMD) at the proximal femur

A selection of regions of interest (ROI) was done from the computational finite element meshes. The selection was made taking into account the ROIs defined by the QDR Explorer (Hologic, Waltham, MA, USA) (Figure 3). The BMD distribution at each ROI, namely at the inferomedial femoral neck (IM), superolateral femoral neck (SL), integral femoral neck (FN), trochanter (TR), and at the intertrochanter (ITR) was then assessed in all femurs. The BMDs' ratios between the defined ROIs - IM:SL, FN:TR and FN:ITR were used to characterize the BMD distribution according to each geometric parameter (FNL, FNW, NSA).

Proximal femur geometry parameters

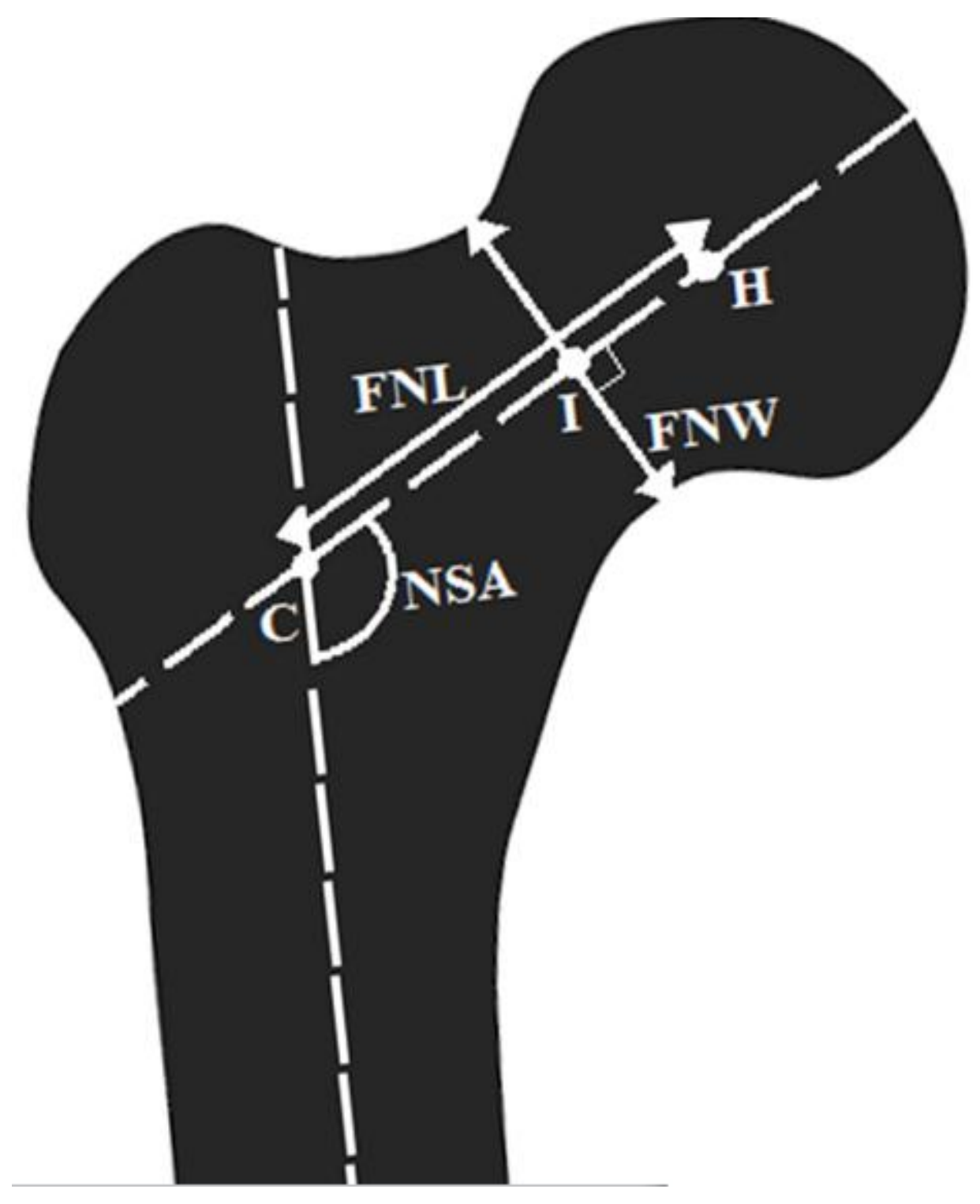

Table 1

	FNL (cm)	NSA (°)	FNW (cm)
Standardized Femur	5.4	119	3.06

Table 2

FNL (cm)	NSA (°)	FNW (cm)
3.4	109	2.9
4.4	119	2.96
5.4	124	3.06
5.9	129	3.16
6.4	134	3.26
6.9	141	3.46

Figure 1

FNL- Femoral Neck Length; NSA- Neck Shaft Angle; FNW-Femoral Neck Width

Finite element modeling and regions of interest

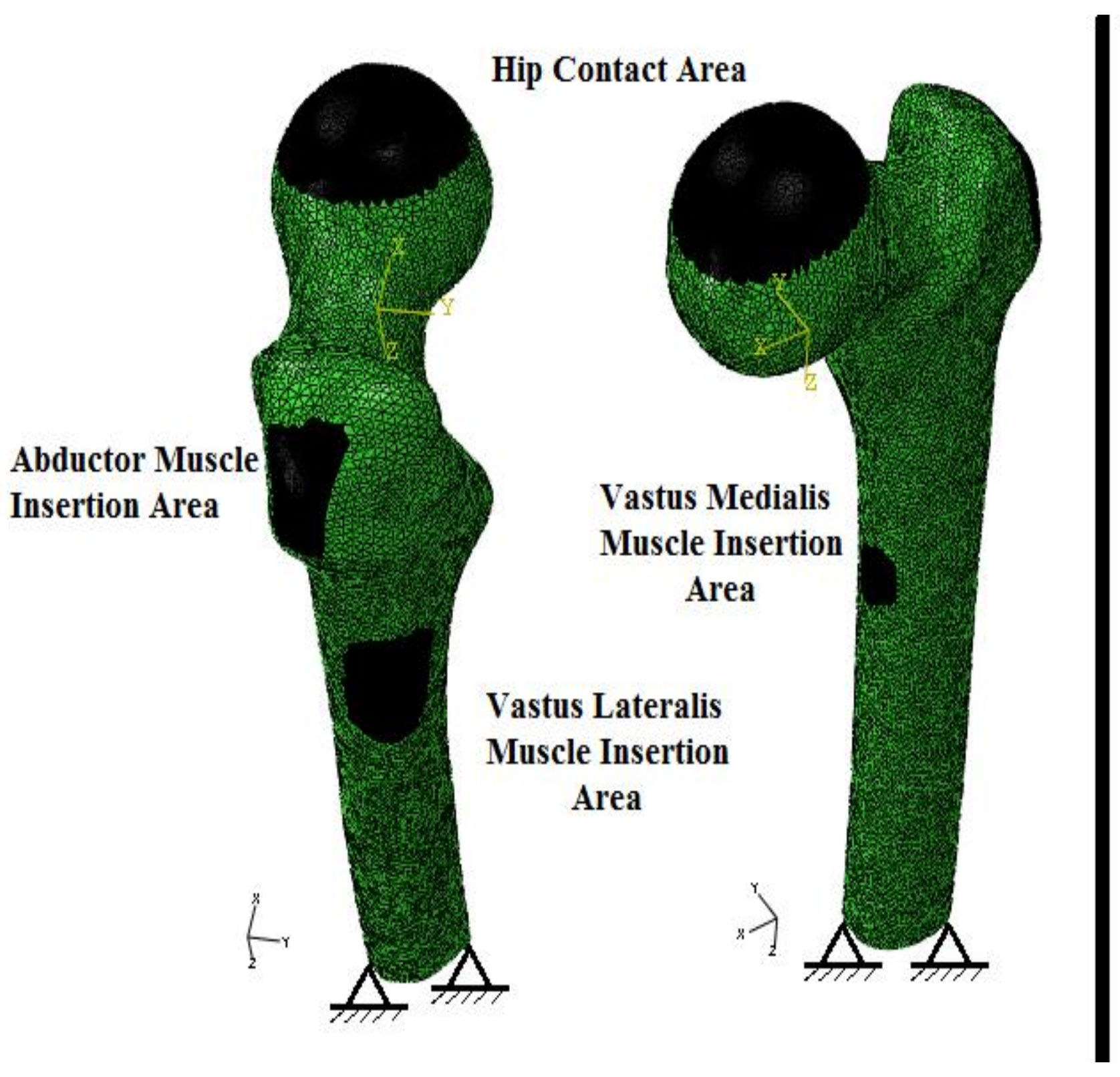

Figure 2

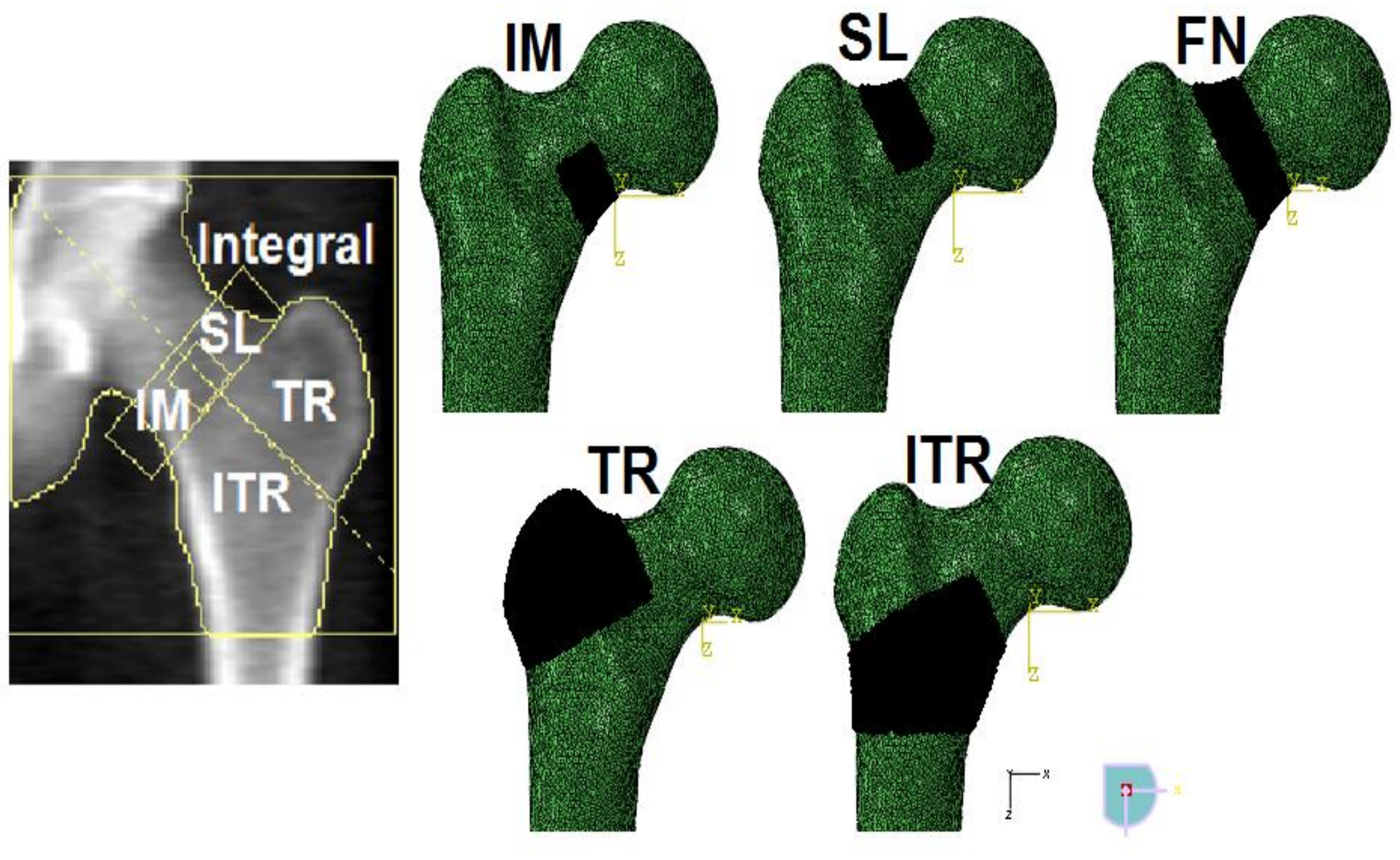

Figure 3

IM- Inferomedial; SL- Superolateral; FN- Integral Femoral Neck; TR- Trochanter; ITR- Intertrochanter

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RESULTS

Simulated proximal femur DXA images

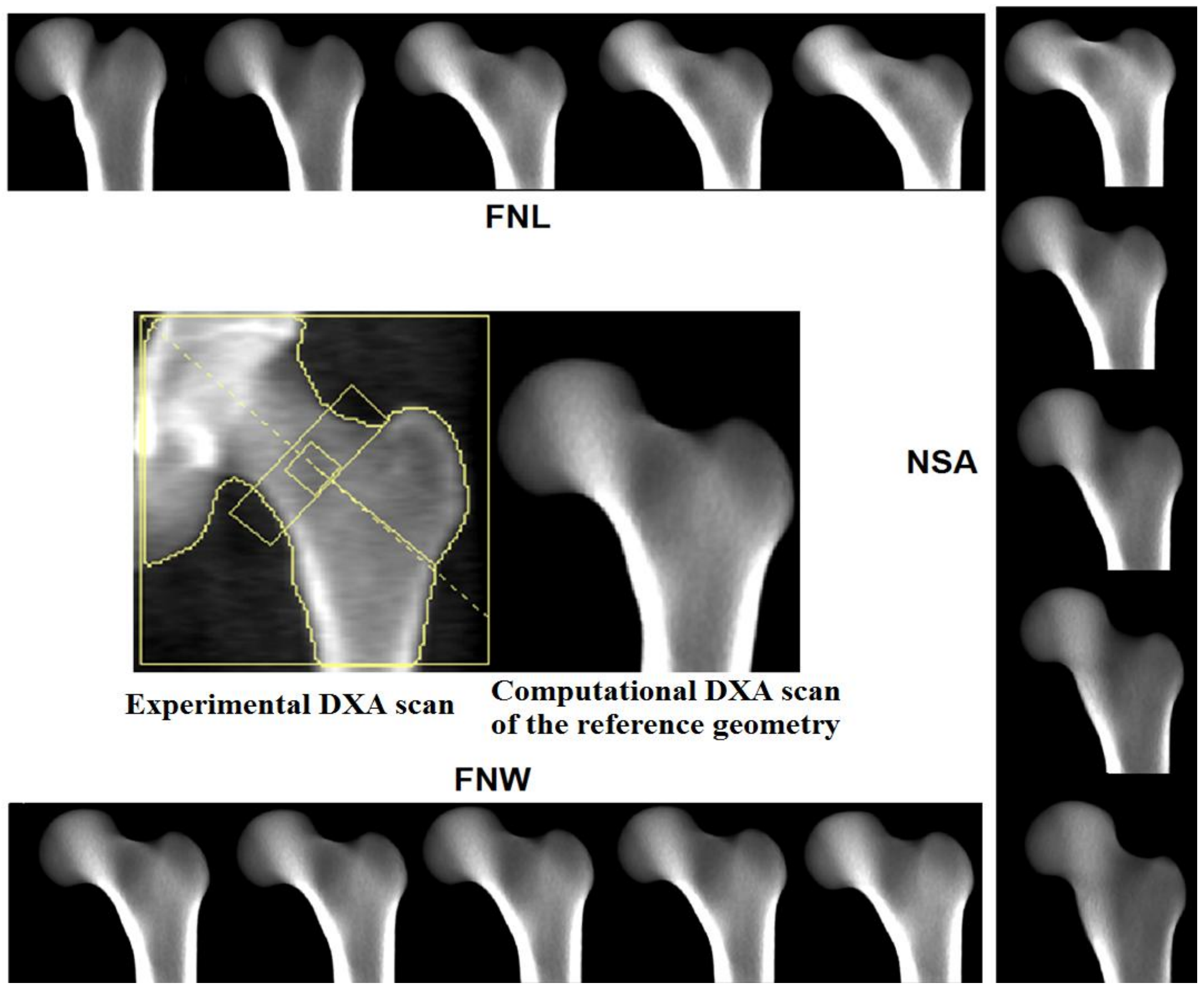

Figure 4

Bone mineral density (BMD) ratios IM:SL, FN:TR, FN:ITR

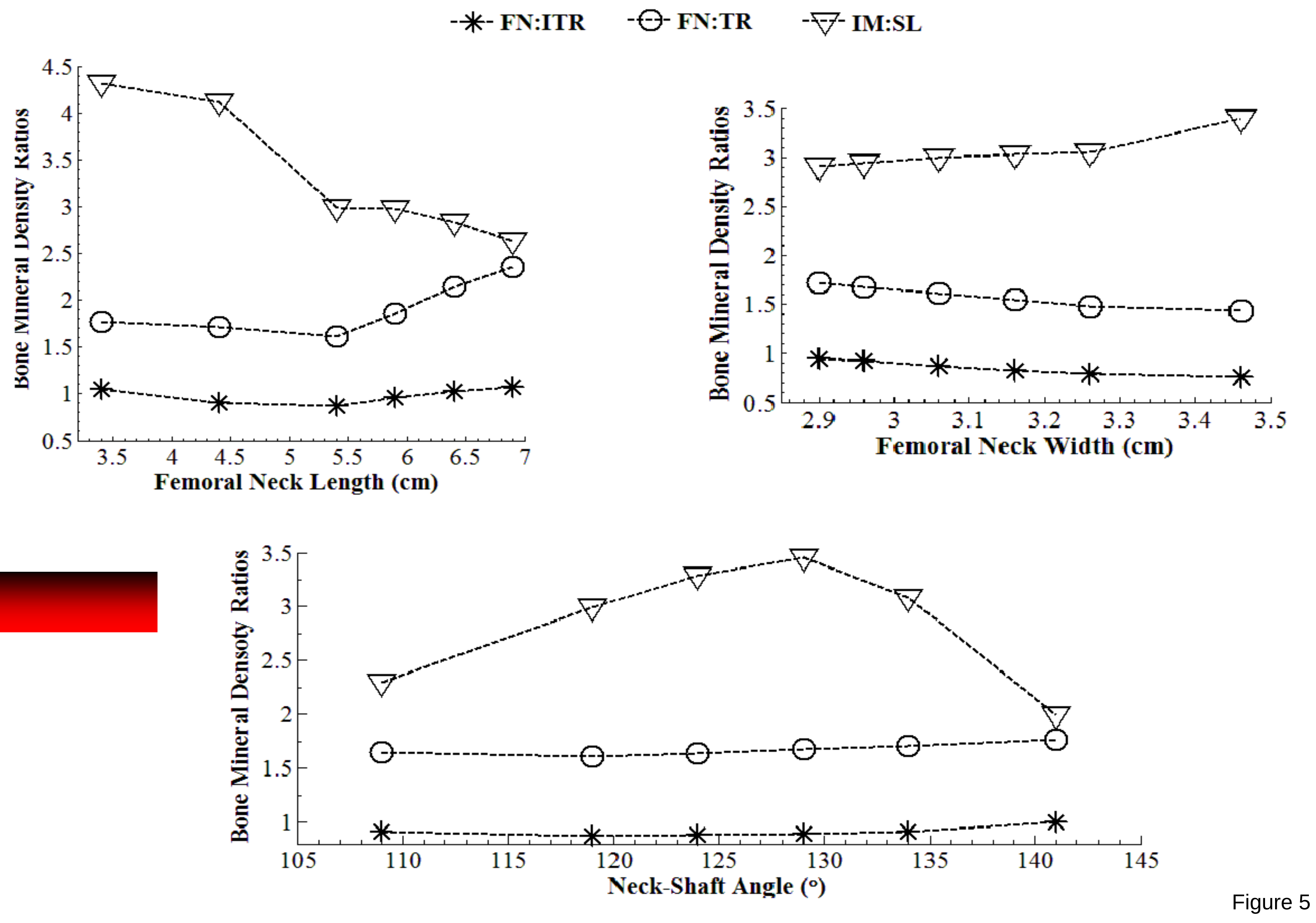

Figure 5

CONCLUSIONS

- ❖ FNL is positively associated with a proportionally greater BMD at the SL region of the femoral neck comparatively to the IM region and therefore might be related with a lower fracture risk superiorly.
- ❖ FNL (≤ 5.4 cm) is positively associated with a proportionally greater BMD at the TR and ITR regions comparatively to the FN region and therefore might be related with a lower fracture risk in those regions regarding the FN region; however the opposite is observed for FNL ≥ 5.4 cm.
- ❖ FNW is positively associated with a proportionally greater BMD at both the TR and the ITR regions comparatively to the FN region and therefore might be related with a lower fracture risk in those regions regarding the FN region.
- ❖ FNW is positively associated with a proportionally lower BMD at the SL region of the femoral neck comparatively to the IM region and therefore might be related with an increase in fracture risk superiorly.
- ❖ NSA (≤ 129) is positively associated with a proportionally lower BMD at the SL region of the femoral neck comparatively to the IM region and therefore might be related with an increase in fracture risk superiorly; however the opposite is observed for NSA ≥ 129 ; only slight differences were observed for the remaining ratios.
- ✓ **Proximal femur geometry** seemed to moderate the influence of mechanical loading associated to gait in bone mineral distribution at the proximal femur, producing structural differences that may account for structural failure. The computational results must be validated against experimental data in order to sustain the findings here exposed.

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