INVESTIGATING BONE DENSITY AND STRENGTH ACROSS SEX AND AGE USING MACHINE LEARNING AND FINITE ELEMENT MODELING

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Introduction

Bone mineral density (BMD) is a key predictor of bone strength, yet many fractures occur in individuals without osteoporotic BMD. While age is an independent risk factor for bone fragility, it remains unclear whether this is driven by intrinsic factors, such as bone structure, or extrinsic factors, such as fall risk. Computed tomography (CT) captures detailed bone density and geometry, which can be combined with finite element (FE) modeling to estimate strength. To apply these methods to large-scale patient cohorts using clinical CT, this study integrated deep learning-based segmentation, FE modeling, and density calibration to assess how the relationship between BMD and bone strength varies across sexes and age groups at the spine and hip.

Methods

A cohort of 1,176 clinical abdominal CT scans was retrospectively obtained from health centers across Alberta. The first lumbar vertebra (L1) and left proximal femur (hip) were segmented from the images using the deep learning segmentation framework nnU-Net [1]. An internal calibration method based on the known densities of air, fat, muscle, blood, and cortical bone was used to convert CT images to bone-equivalent densities [3]. For this calibration, the autochthonous and gluteal muscles, aortic and iliac arteries, and subcutaneous fat were segmented using a deep learning model [2], while air and cortical bone were segmented using thresholding and connected components analysis. The mean CT value of each tissue was used for internal calibration and integral BMD (mg/cc) was measured. For FE analysis, each image voxel was converted to an 8-node hexahedral element with a Poisson's ratio of 0.3 and Young's modulus was derived from calibrated density using a power-law. The L1 and hip segmentations were aligned using iterative closest point registration for compressive loading and sideways fall, respectively. Simulated PMMA endcaps were added to the vertebral body and femoral head, and 1% compression was applied. Failure load (F.Load; N) and stiffness (N/mm) were estimated (FAIM, Numerics88 Solutions). Participants were categorized into age groups: under 50 years, 50 to 65 years, and over 65 years, to examine age-related changes. Mann-Whitney U tests with Bonferroni correction were used to assess differences in F.Load, stiffness, and BMD by sex and age. Linear regression models and coefficient of determination (R^2) were used to examine relationships between BMD, F.Load and stiffness across sexes and age groups.

Results

The cohort consisted of 277 males (65.3 ± 11.3 years) and 899 females (62.2 ± 9.4 years). Bone stiffness and F.Load were 15% and 29% lower, respectively, in females than males at the hip and 24% and 28% lower at L1 ($p < 0.01$). The magnitude of these differences exceeded that of BMD, which was significantly lower at the spine ($p < 0.05$) but not at the hip ($p = 0.73$).

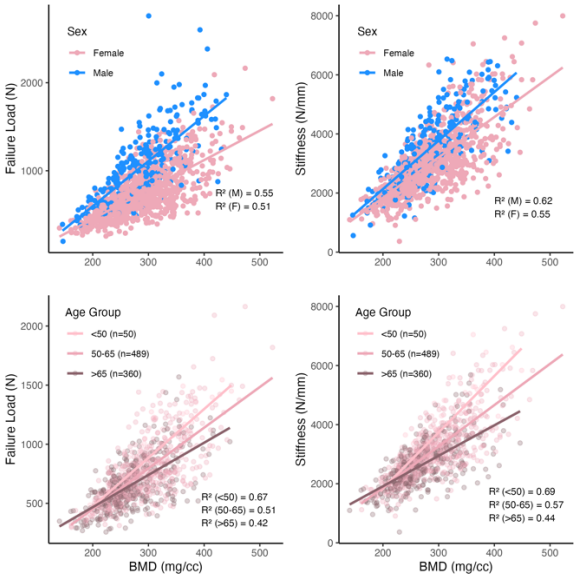

Figure 1: Linear regression plots demonstrating the relationships between BMD, F.Load and stiffness.

The relationships between BMD and stiffness, along with BMD and F.Load, were significantly different between sexes ($p<0.001$), with males demonstrating stronger correlations. In females, the relationship between BMD and stiffness varied across the three age groups ($p<0.01$), with the under 50 group having the strongest correlation. The change in relationship between BMD and F.Load was only significantly different between the under 50 and over 65 groups ($p<0.01$), with F.Load being 28% lower in the over 65 age group.

Discussion

Our study integrates machine learning, density calibration and FE modeling with large-scale population data to show that individuals with similar BMD can exhibit differences in bone strength and stiffness based on sex and age. This suggests BMD alone may be insufficient for detecting bone fragility, particularly in postmenopausal women. Incorporating bone strength and stiffness could improve fracture risk identification and osteoporosis screening.

References

1. Isensee et al, Nat Methods, 18:203-211, 2021.
2. Wasserthal et al, Radiology: AI, 5:e230024, 2023.
3. Michalski et al, Med Eng Phys, 78:55-63, 2020.