Age-related Emergence of Deleterious Buckling Ratio in the Femoral Neck Fails to Maintain the Coupling with Predominant Collagen Fiber Orientation and Osteon Morphotypes Seen in Younger Bones

Chad S. Mears, B.S., Kendra E. Keenan, M.P.H., Tanner D. Langston, Colton M. Phippen, Scott M. Litton, S. Taylor Brady, Roy D. Bloebaum, Ph.D., John G. Skedros, M.D..
University of Utah, Salt Lake City, UT, USA.

Disclosures: **C.S. Mears:** None. **K.E. Keenan:** None. **T.D. Langston:** None. **C.M. Phippen:** None. **S.M. Litton:** None. **S.T. Brady:** None. **R.D. Bloebaum:** None. **J.G. Skedros:** None.

Introduction: The age-related exponential increase in femoral-neck (FN) fracture risk is not fully explained by the corresponding decrease in bone mineral density of the FN. Aging affects FN fracture risk independently of bone mineral density, suggesting that there are other important age-related changes that must be considered [1,2]. Yoshikawa et al. [3] and Mayhew et al. [1] showed that bone loss occurs preferentially on the superior aspect of the FN. This region is under minimum mechanical stress during walking, whereas a fall on the hip reverses the stress pattern causing high compressive stresses at the superior FN (Fig. 1). Therefore, age-related bone loss occurs in the specific location that is most highly stressed by a fall. Mayhew et al. [1] propose that structural changes in the FN occur independently of osteoporosis and contribute greatly to the risk of FN fracture. They noted that bone loss at the superior aspect of the FN could make the bone susceptible to failure by buckling. Buckling is most commonly associated with slender columns. A column loaded in compression can bow laterally and, if the lateral displacement of the column surpasses a critical amount, the column will collapse. Mayhew et al. [1] show that cortical thinning occurs preferentially at the posterior-superior (Sup) FN whereas the inferior (Inf) cortical shell gains thickness with age. (The latter change is thought to be an adaptive response to walking, which causes large compressive stresses on the inferior FN.) If the FN does indeed behave like a shell, then the Sup region should be at high risk of buckling during a sideways fall. In the present study we advance our previous research on histomorphology of the FN with aging [4] by seeking to determine if there is evidence that the age-related increased risk of buckling might be curbed by compensatory changes in bone material organization.

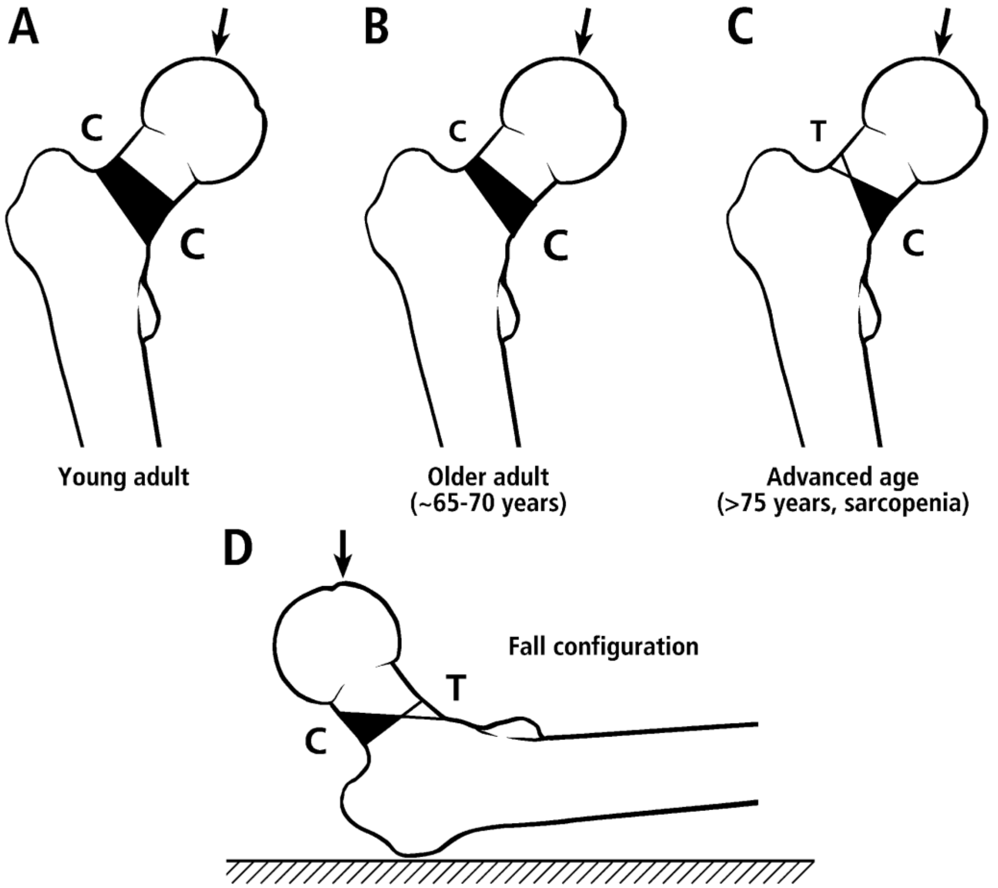
Methods: 29 human FNs (3 M, 26 F; 18-95 yrs) were embedded in methacrylate and a mid-transverse section from each was mounted on glass and ultramilled (100µm). 50X circular polarized light images were obtained in octants. The buckling ratio for each femoral neck was calculated as 1⁄2 the outer diameter of the femoral neck measured in the plane of bending (Sup.-Inf. axis) divided by the average cortical thickness in all eight (octant) locations [5]. Predominant CFO was expressed as the mean gray-level of each image, and population densities of complete secondary osteons (OPD) and their morphotype scores (MTS) were also quantified [4,6]. Osteon morphotypes are based on collagen/lamellar patterns that correlate with regional differences in habitual strain mode (compression vs. tension) [6]. We also quantified: fractional area of secondary bone (FASB, %), porosity (%), osteon area (On.Ar, µm^2), osteon circularity (On.Cr) (1.0 = perfect circle), Haversian canal area (HC.Ar), Haversian canal circularity (HC.Cr), osteon formation/infilling (On.Ar - HC.Ar), and cortical thickness (CT, mm). The regions quantified were defined as the Sup cortex (posterior, posterior-superior, superior;

combined data) and Inf cortex (anterior, anterior-inferior, inferior; combined data). These groups are based on data showing the posterior-superior to anterior-inferior axis is where fracture resistance is most compromised in the elderly [1].

Results: In the table are results of the correlation analyses of the buckling ratio with age and with Sup/Inf ratios of the microstructural parameters in: (1) all bones, (2) <60 year-old bones, and (3) ≥ 60 year-old bones. Across the age range of the younger bones, the buckling ratio showed no significant change ($r=0.01$, $p=0.9$). But the variation in buckling ratio in the younger bones did show significant correlations with Sup/Inf ratios of CFO, osteon MTS, and osteon formation. By contrast, in the older bones: (1) the buckling ratio not only substantially worsened but with advanced age it also exceeded the threshold that is considered deleterious (i.e. > 10) [5], and (2) the variation in the buckling ratio failed to show any correlation with the Sup/Inf ratios of any microstructural characteristics. Buckling ratios for younger bones had a mean of 8.6±1.3 (±S.D.) and for older bones a mean of 10.7±2.1 ($p<0.01$).

Discussion: The lack of microstructural associations with deleterious increases in buckling ratios of the older bones may represent failure to retain the compensatory/adaptive mechanisms seen in the younger bones. We argue that in younger bones the overall load-carrying capacity of the FN is enhanced by the coupling of the adequate buckling ratio with Sup/Inf variations in CFO, osteon MTS, and osteon formation/infilling. By contrast, the lack of coupling of the buckling ratio with the Sup/Inf variations in these important microstructural characteristics likely contributes to the elastic instability that occurs in the FN with aging [1,2,5]. This is an important observation because CFO and osteon MTS have paramount importance in the energy absorption of bone [7] and these osteon formation dynamics become deficient in the aged FN [2]. This may reflect age-related underloading of the Sup FN cortex to an extent that fails to stimulate the adaptive response [1]. If these interpretations are correct, then age-related degradation in FN strength and load-carrying capacity is achieved by a synergism of structural and material characteristics in younger bones in ways that are not often considered in studies of the factors that lead to increased FN-fracture risk with aging.

Significance: With aging the most compromised region of the femoral neck is the posterior-superior cortex. Correcting this problem will likely require enhancing the material properties of the bone along with the supplementation of bone mass along the posterior-superior to anterior-inferior axis.



The hypothesized changes in loading from young (A) to elderly (C). When an aged (B) or elderly (D) person falls the habitual low-level compression (B) or tension (C) typically experienced by the superior femoral neck is then overloaded in high compression stress. These age-related low-level strains contribute to thinning of the femoral neck. RESULTS OF THIS STUDY SUGGEST THAT THE AGE-RELATED LOADING CHANGE SUGGESTED IN "B" MIGHT OCCUR, BUT NOT THAT SHOW IN "C".

Correlation Analyses with the Buckling Ratio [only significant correlations are shown]

	r value	p value
All bones		
Age	0.6	<0.01
Young bones (<60 yrs.)		
MTS Sup/Inf Ratio	0.72	<0.01
CFO Sup/Inf Ratio	0.52	0.03
On.Form Sup/Inf Ratio	0.65	<0.01
Old bones (≥60 yrs.)		
Age	0.57	0.05

MTS = osteon morphotype score; On.Form = osteon formation/infilling; CFO = predominant collagen fiber orientation; Sup = superior cortex (i.e. data from Post, P-S, Sup combined); Inf = inferior cortex (i.e. data from Inf, A-I, Ant combined).

ORS 2015 Annual Meeting
Poster No: 0631