A Novel Mesh-Free Method for Accurately Simulating the Crushing and Cracking Behavior of Trabecular Bone Tissue With a Wide Range of Clinically Relevant Bone Mineral Density Values

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Purpose: Accurate simulation of trabecular bone biomechanics is critical to the development of orthopaedic implants resistant to postsurgical migration, particularly for patients with osteoporosis. Conventional mesh-based simulation techniques such as finite element analysis (FEA) are limited in their ability to model the crushing, cracking, fragmentation, and compaction phenomena that occur during implant migration. Recent studies have shown that newer mesh-free simulation techniques, such as smoothed-particle hydrodynamics (SPH), can overcome many such limitations, although validation was only completed for a narrow range of bone densities and morphologies. In the present study, an improved mesh-free simulation method was developed capable of accurately simulating the cracking, fragmentation, and compaction of trabecular bone specimens with a wide range of bone densities and morphologies. Results were validated by examining the concordance between physical and simulated results when crushing human cadaveric trabecular tissue.

Methods: Cylindrical trabecular bone specimens (n = 22) with height of 12 mm and radius of 3.7 mm were extracted from the proximal heads of 9 fresh-frozen human cadaveric humeri (7 female, 2 male donors; mean age 73.7 years; range, 45-86). MicroCT scans of these specimens (15 μm/pixel) were used to measure volumetric bone mineral density (vBMD; range, 0.040–0.214 gHA/cm3) and to construct mesh-free models for simulation. Physical and simulated specimens were compressed under axial loading to 20% to 30% of their original height while recording force-displacement data. To improve concordance with the physical data, simulation parameters were systematically iterated to develop an equation (power law) that adjusted the Young modulus for each specimen according its vBMD score.

Results: Across all vBMD values (0.040-0.214 gHA/cm3), the concordance correlation coefficient (CCC) between physical and simulated force-displacement data was 0.762, with a 95% confidence interval (CI) of 0.746-0.777, a Pearson ϱ (precision) value of 0.911, and a bias correction factor Cb (accuracy) value of 0.837. For the 15 least-dense specimens (vBMD values of 0.040-0.150 gHA/cm3), the CCC was 0.8792 (95% CI 0.866-0.891, ϱ = 0.936, Cb = 0.940). From the literature, this range of density (0.040-0.150 gHA/cm3) accounts for between 80% and 99.9%, 91%, and 87% of the trabecular bone tissue present in the proximal humeri, proximal femora, and lumbar vertebrae of postmenopausal women, respectively.

Conclusion: The improved mesh-free model presented here accurately simulated the behavior of trabecular bone specimens with a range of densities representing the majority of trabecular bone present in the humeri, femora, and lumbar vertebrae of postmenopausal women. Further research is necessary to improve accuracy for denser tissue. This is the first such model of which the authors are presently aware.