FEMORAL NECK BONE FRATURE TOUGHNESS AND BONE STRENGTH RELATIONSHIPS UNDER HIGH-RATE IMPACT LOADING

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Background

Bone mineral density (BMD) is often used to predict hip fractures due to its association with femoral neck bone strength (R^2 from 0.42 to 0.80)[1]. However, most people who suffer hip fractures don't have low BMD, suggesting other factors are involved. While the fracture toughness of cortical bone correlates with the integrity of bone's organic phase (mostly collagen), the link between tissue-level fracture toughness and structural-level bone strength is under-studied, especially under the high-rate loading associated with falls. The goal of this study was to investigate the relationship between femoral neck bone strength and femoral neck fracture toughness when tested under high-rate loading. Specifically, we hypothesized that fracture toughness results from high-rate loading tests of inferior femoral neck samples would be positively associated with femoral neck bone strength.

Methodology

Ten fresh-frozen cadaveric femurs (five matched-pairs) underwent DXA scans to extract femoral neck BMD. Right femurs were mounted in a drop tower impact simulator and subjected to simulated lateral impacts until failure; bone strength was defined as the peak impact force. Single edge notch bending (SENB) specimens where extracted from the inferior femoral neck of the left femurs, as this region experiences tension during lateral hip-impacts, and is one of the most common fracture sites[2]. Specimens were mounted in three-point bending within a micro-mechanical testing system and were subjected to high strain rate (40 mm/s) loading until failure (Figure 1). High-speed microscopy-enabled videography captured crack propagation, which was combined with loading data to compute fracture toughness (K_q and J_{Ic}). Multi-variate regression was used to investigate factors that predicted bone strength, including age, BMD, and fracture toughness metrics.

Results and Discussion

Strong relationships were observed between bone strength and K_q (R^2=0.828, β=0.933, p=0.02) and BMD (R^2=0.835, β=0.936, p=0.02). Analysis revealed that K_q + BMD was the most predictive model (R^2=0.994, K_q β=0.528, BMD β=0.539, p=0.003), outperforming all other models. In most cases, J_{Ic} as a measure of fracture toughness yielded slightly weaker models than those with K_q, with the exception of age + J_{Ic} (R^2=0.869, age β =0.601, J_{Ic} β = 0.731, p = 0.07); though not significant, age was observed to be more strongly related with J_{Ic} than Kq.

These findings provide the first insight into the relationship between fracture toughness and femoral neck bone strength under high-rate loading, and suggest that fracture toughness metrics may be complementary predictor of hip fractures to BMD. Our results suggest that while there may be some degree on non-linearity captured by JIc, the linear elastic behaviour captured by Kq seem to the most appropriate fracture toughness metric to relate high-rate loading fracture toughness experiments to femoral neck bone strength in the context of fall-related hip fractures.