Relating Impact Velocity and Loading Rate to Femoral Bone Strength in Biofidelic Simulated Lateral Impacts

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Due in part to the aging demographics in most developed nations, fall-related hip fractures are an increasing concern from both economic and public health perspectives. Costing an estimated 650 million dollars each year in Canada alone [1], there is a concerted effort to better understand the underlying mechanics of fall related hip fractures to better predict, and ultimately prevent, their occurrence. While predictions for bone strength based on BMD exist, these predictive equations are based on measures of bone strength derived from constant displacement-rate experiments [2,3]. Therefore, the goal of this study was to quantify the strength of cadaveric human femora in simulated lateral impacts with physiologically relevant impact velocities and stiffness conditions, as well as characterize the relationship between loading rate and impact velocity.

Five human cadaveric femora (specimen age range 27-80 years) underwent hip-specific DXA scans to extract femoral neck BMD. Specimens were then placed in a test system which incorporated physiologically-based pelvic mass and stiffness properties [4], and subjected to simulated lateral impacts at incrementally increasing drop heights until failure occurred (heights selected to create approximate impact velocities of 0.5 m/s to 4.5 m/s, in 0.5 m/s increments). Peak force, loading rate, and impact energy were extracted from each trial. Fracture force (representing bone strength) was noted for each fracture trial.

Specimen-specific and pooled Pearson correlations were computed to investigate the following relationships: 1) impact velocity and loading rate, 2) impact energy and loading rate, 3) fracture force and BMD, and 4) fracture force and specimen age. A non-linear regression model was developed to predict loading rate from impact velocity.

Four specimens fractured at the drop height used to elicit 4.5 m/s impacts (actual mean impact velocity = 4.13 m/s, SD = 0.04 m/s), with a mean fracture force of 4730 N (SD = 468 N), and a mean loading rate of 103.4 kN/s (SD = 9.3 kN/s). These specimens had a mean areal BMD of 0.691 g/cm^2 (SD = 0.068 g/cm^2). One specimen fractured during the 1 m/s condition, with a fracture force of 1804 N and a loading rate of 69.6 kN/s (BMD = 0.513 g/cm^2). A strong correlation was observed between fracture force and BMD for the five specimens ($R^2 = 0.876$, $p < 0.01$). For both the specimen-specific and pooled analyses, correlations between impact velocity and loading rate were stronger than those between impact energy and loading rate, albeit not all significant (Table 1). A non-linear regression model was developed to predict loading rate from impact velocity ($R^2 = 0.740$) (Figure 1).

Our findings confirm the link between femoral neck BMD and bone strength when tested with a biofidelic test system (incorporating biofidelic pelvic stiffness and effective mass) at physiologically relevant impact velocities. Furthermore, we characterized the non-linear relationship between loading rate and impact velocity. This work may support future load-controlled mechanical tests of femoral bone strength. Furthermore, this study provides insight into the impact dynamics of lateral impacts, towards the ultimate goal of better prediction and prevention of fall related hip fractures.

References: [1] Wiktorowicz et al. (2001). Osteoporos Int, 12(4): 271-78.; [2] Courtney et al (1994). Calcif Tissue Int, 5(1): 53-58.; [3] Roberts et al. (2010). Bone, 46: 742-46.; [4] Robinovitch et al. (2009). Osteoporos Int, 20(12):1977-88

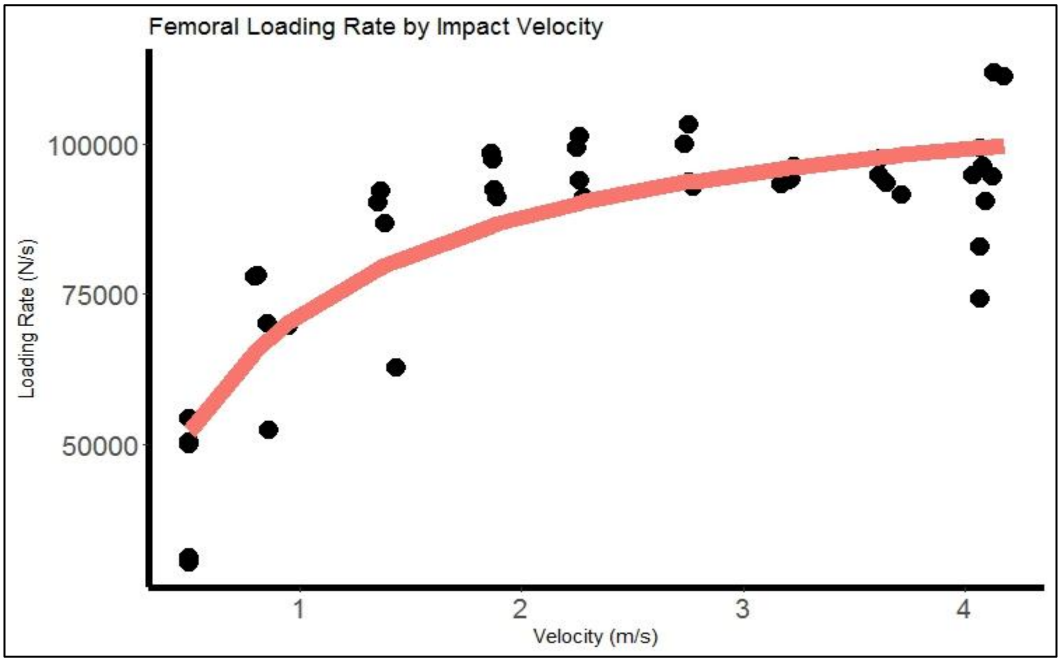

Figure 1: Femur loading rate versus impact velocity. Black dots are individual data points (all specimens, all trials), while the red line is non-linear regression line of best fit ($y = 113700*x/(0.5897+x)$)

Table 1: Specimen specific and pooled correlation results between: 1) loading rate and impact velocity, 2) loading rate and impact energy, 3) fracture force and BMD, and 4) fracture force and age. Significant correlations ($p < 0.05$) are bold. Specimen specific correlations could not be calculated for specimen 5 (due to fracture occurring during the second trial).

Loading Rate	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Pooled
Impact Velocity	**$R^2 = 0.521$ ($p = 0.018$)**	**$R^2 = 0.752$ ($p = 0.001$)**	$R^2 = 0.227$ ($p = 0.139$)	**$R^2 = 0.465$ ($p = 0.030$)**	**$R^2 = 0.494$ ($p < 0.001$)**
Impact Energy	$R^2 = 0.355$ ($p = 0.069$)	**$R^2 = 0.589$ ($p = 0.009$)**	$R^2 = 0.080$ ($p = 0.399$)	$R^2 = 0.274$ ($p = 0.121$)	**$R^2 = 0.326$ ($p < 0.001$)**
Fracture Force					
BMD					**$R^2 = 0.876$ ($p = 0.019$)**
Age					$R^2 = 0.399$ ($p=0.253$)