Subject-Specific Curved-Beam Modelling of the Proximal Femur: The Relationship between Femoral Geometry and Stresses during Lateral Falls on the Hip

Steven P. Pretty, Iris C. Levine, Andrew C. Laing
Department of Kinesiology, University of Waterloo, Waterloo, ON

Introduction: Clinical femoral geometry elements has been linked to epidemiological hip fracture risk [1]. The underlying mechanisms have been attributed to fracture strength [1], however, geometry also influences peak stress magnitude and location [2]. The primary goal of this project was to determine whether clinical femoral geometry elements, previously related to femur fracture tolerance, correlate with simple beam model femoral stresses during a simulated lateral fall. We hypothesized that peak stress would correlate with femur geometry, particularly the angle between the femoral neck and shaft and the femoral neck length.

Methods: Seventeen young females (mean(SD) age = 24.4(3.2) years) underwent a pelvis-release protocol [4], simulating a 1 m/s lateral impact onto a force plate (3500 Hz; OR 6-7, AMTI). Peak force (FI) was extracted and averaged across three trials. Femur geometry was obtained from right hip dual-energy x-ray radiographs (Figure 1a; Hologic Discovery QDR). Specifically, we measured the femoral neck width (NW), intertrochanteric width (TW), femoral shaft width (SW), femoral neck axis length (FNAL), neck-shaft angle (NSA), and cortex width at the femoral shaft (FSC) and intertrochanteric regions (CFC). Subject-specific curved-beam proximal femur models were generated, consistent with Yang et al. [3]. Peak stresses were determined for three critical cross-sections (Figure 1b): Narrow Neck (NN), Intertrochanteric (IT), and Femoral Shaft (FS).
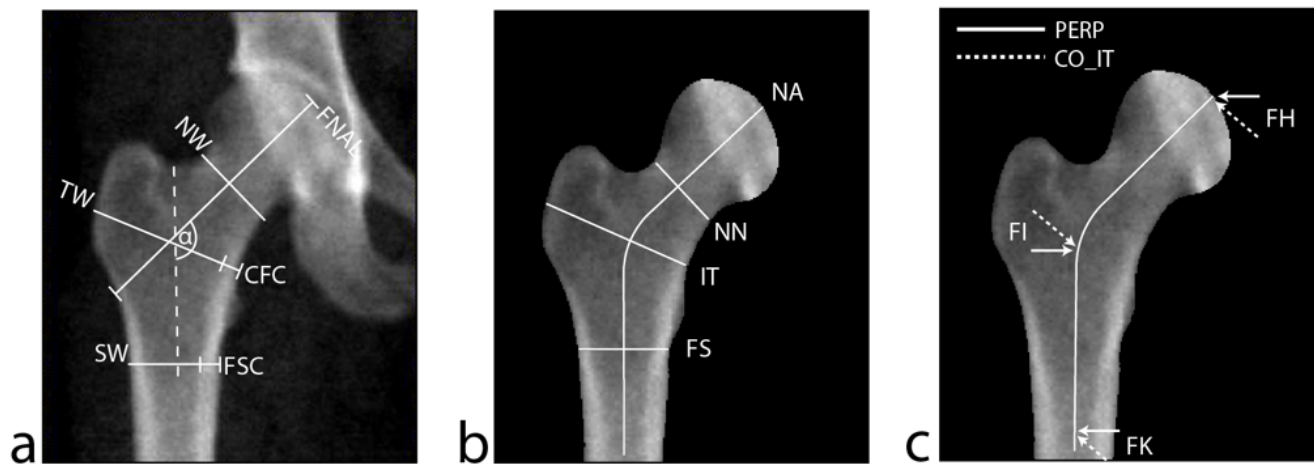

Figure 1: a) Digitized femur geometry elements: Neck width (NW), trochanteric width (TW), shaft width (SW). Calcar femoral cortex width (CFC) is measured along TW; Femoral shaft cortex width (FSC) is measured along SW. Femoral neck axis length (FNAL) is the distance between the inferior greater trochanter and the medial apex of the femoral head. Neck-shaft angle (NSA, α) is the angle between the femoral neck and shaft axes. **b)** Curved beam axis and critical cross-sections: Neutral axis (NA) is defined by two straight lines through the femoral shaft and neck connected by a curved line through the trochanteric region. Three critical cross-sections at the narrow neck (NN), intertrochanteric region (IT), and femoral shaft (FS) corresponding with common fracture sites. **c)** Fall loading conditions: Impact force (FI) extracted from experimental fall simulations is applied through the neutral point of the femur perpendicular to the femoral shaft axis (Loading condition 1: PERP), or coincident with the IT cross-section (Loading condition 2: CO_IT). Femoral head (FH) and knee (FK) reaction forces are applied parallel to FI to satisfy static equilibrium.

Two loading conditions were simulated, corresponding with a lateral fall onto the hip (Figure 1c): impact vector 1) directly perpendicular to the femoral shaft (PERP) and 2) coincident with the intertrochanteric cross section (CO_IT). In both conditions, the femur is represented as three beams with fixed connections supported by a roller at the femoral head and a pin at the knee. Single-tailed bivariate correlations were performed to assess the relationship between femoral geometry elements and peak stresses at each cross-section.

Results: For both loading conditions: NN peak stress was correlated positively with NSA ($p<.001$, Figure 2), and negatively with TW ($p<.05$); IT peak stress was negatively correlated with CFC ($p<.01$); and FS peak stress was negatively correlated with TW ($p<.001$) and FNAL ($p<0.05$). SW, NW, and FSC were not significantly correlated with stresses at any cross-section.
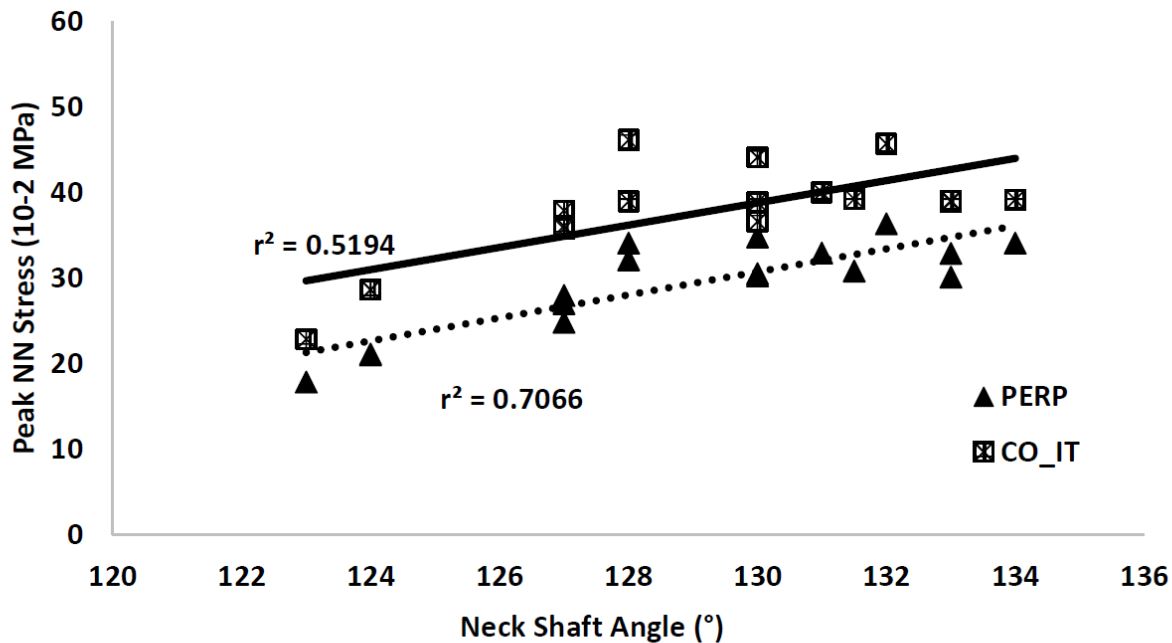

Figure 2: Relationship between NSA and peak stress at the NN cross-section for PERP and CO_IT loading Conditions

Discussion: Although impact force is independent of femoral geometry [4], we demonstrated in this study that femur geometry is related to tissue level stresses using a simple curved-beam modeling approach. Wider NSA was associated with increased stresses at the femoral neck, supporting previous epidemiological studies linking a wider NSA with increased fracture risk [5]. A number of femoral geometry variables (SW, NW and FSC) previously related to fracture risk did not correlate with femoral stresses; these variables likely modulate fracture risk primarily through their effect on fracture strength [1]. Relationships were consistent across the two impact configurations simulated, but future work should evaluate these relationships with loading conditions congruent with additional biofidelic impact configurations. We utilized experimental impact force magnitude, however, more detailed impact loading conditions (anatomical point of application and line of action) may better capture the potential influence of femoral geometry on generation of stress in the proximal femur [4].

References

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