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Influence of Fall Simulation Paradigm, Sex, and Trochanteric Soft Tissue Thickness on Femoral Neck Stresses and Fracture Risk during Lateral Falls

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Utilizing a participant-specific approach, the dual importance of femur morphology and impact dynamics on hip fracture risk were observed

Introduction

- Hip fracture risk during a fall can be modulated through impact dynamics and/or underlying femur morphology [1]
  - Risk assessment efforts have focused on the latter
- An approach sensitive to both skin-surface impact dynamics as well as underlying femur morphology could provide additional insight into the mechanical nature of clinical risk factors

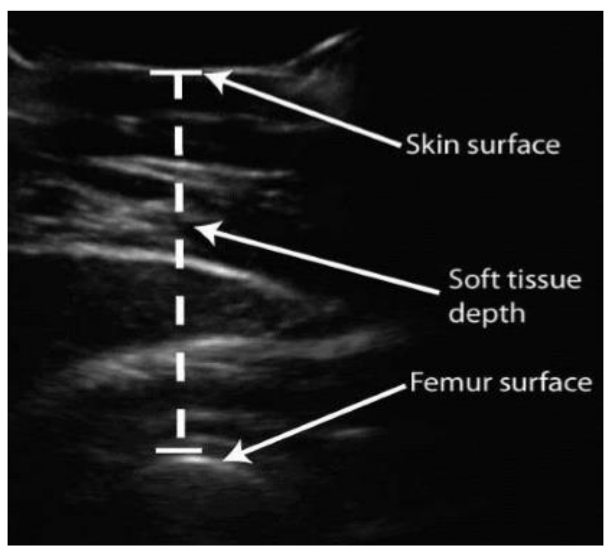

Figure 1: Ultrasound measurement of trochanteric soft tissue thickness

- **Purpose:** Evaluate the influence of fall simulation paradigm (FSP), sex, and trochanteric soft tissue thickness (TSTT) **on femoral neck stresses and fracture risk index (FRI)**
  - Insights gained through coupling of experimental data and tissue-level models could inform the development of protective devices and increase the accuracy of clinical screening tools.

Methods

- 33 young adults (16 male) were stratified into TSTT groups via ultrasound imaging (Figure 1)
- A series of FSP and dual-energy x-ray imaging (DXA) were utilized to enable estimation of femoral neck stresses and FRI

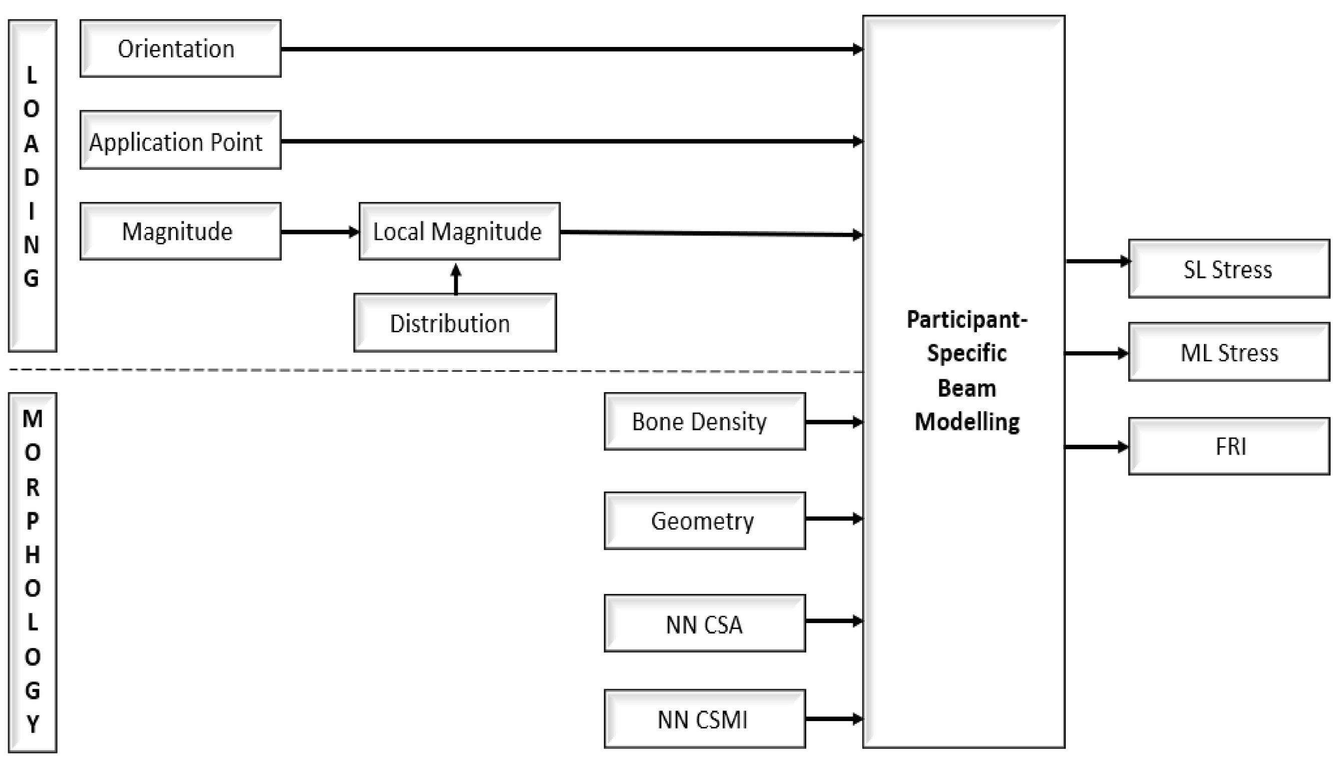

Figure 2: Experimental FSP data and DXA imaging were utilized to enable participant specific beam modelling

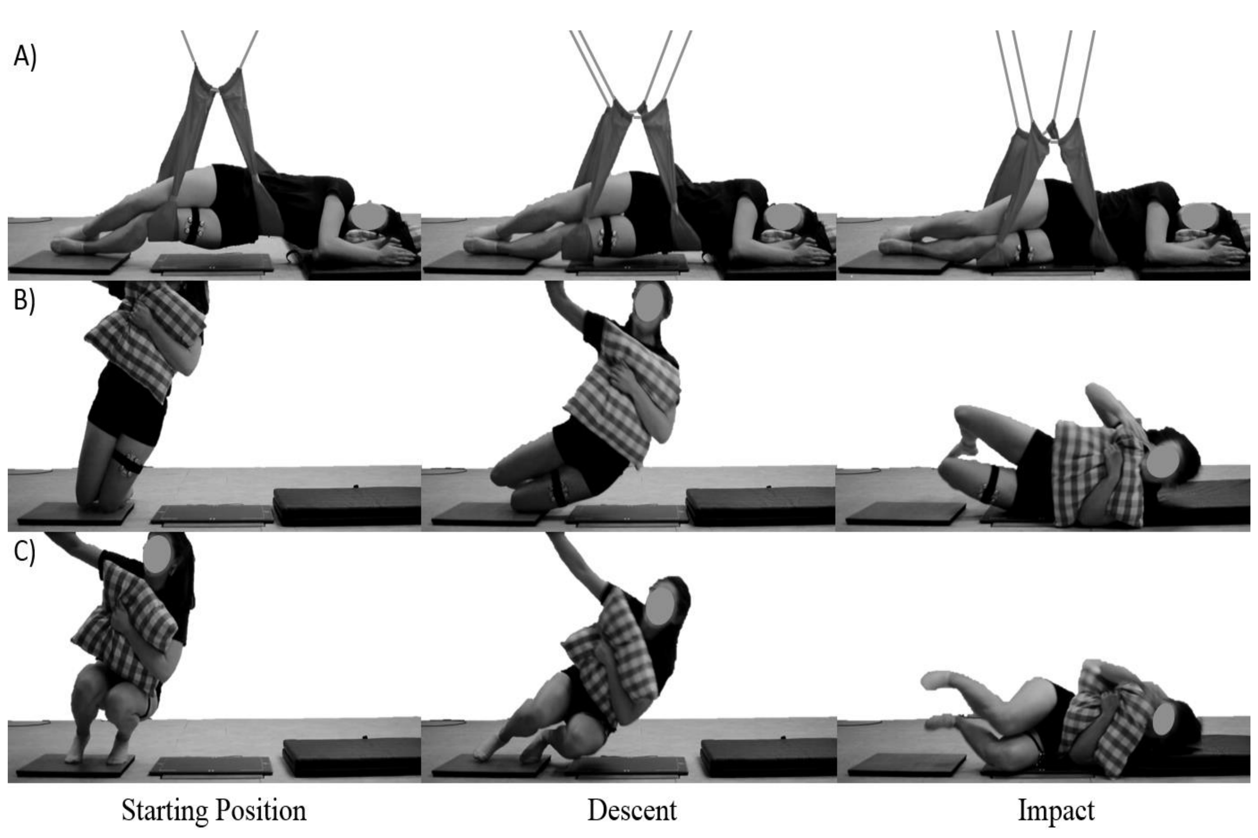

Figure 3: Phases of a) pelvis, b) kneeling, and c) squat release FSP. The pelvis release represents a purely vertical impact, whereas kneeling and squat releases involve lateral and rotational motions.

Fall Simulations:
Participants completed a series of FSP (Figure 3), encompassing the variability of falls observed in older adults. Kinematics and kinetics of the impacting (left) thigh were collected. At the instant of peak force, the net impact vector orientation, anatomical point of application, and local force magnitude over the greater trochanter (circular r = 5 cm) were extracted.

Modelling: Participants underwent left hip DXA imaging. Participant specific beam models were generated through extraction of femur morphology [2] and application of experimental loading conditions. Femoral neck stresses at the superior-lateral (SL) and inferior-medial (IM) cortices, as well as a cross-sectional FRI were calculated for each experimental fall simulation (Figure 4).

$$t_i = aBMD_i/\rho_b$$

$$CSA = \Delta L \sum_{i=1}^{i=N} t_i$$

$$y_c = \sum t_i\, y_i / CSA$$

$$CSMI = \Delta L \sum_{i=1}^{i=N} t_i (y_i - y_c)^2$$

$$Compressive\ \sigma_Y = \begin{cases} 85.5\rho_{app}^{2.26}, & \rho_{app} \le 0.355\ g/cm^3 \\ 38.5\rho_{app}^{1.48}, & \rho_{app} > 0.355\ g/cm^3 \end{cases}$$

$$Tensile\ \sigma_Y = \begin{cases} 50.1\rho_{app}^{2.04}, & \rho_{app} \le 0.355\ g/cm^3 \\ 22.6\rho_{app}^{1.26}, & \rho_{app} > 0.355\ g/cm^3 \end{cases}$$

$$\rho_{app} = \frac{vBMD}{0.68172} \qquad vBMD = 1.20 * \frac{aBMD}{NW} + 0.0242$$

$$\sigma_i = \frac{Fa}{CSA} + \frac{M(y_i - y_c)}{CSMI}$$

$$FRI = \frac{\sum_{i=1}^{i=N} \frac{\sigma_i}{Tensile/Compressive\ \sigma_{Yi}}}{N}$$

Figure 4: Proximal femur beam modelling. Femur cross sectional properties and geometry were extracted and experimental loading conditions applied to enable calculation of normal stress along the femoral neck. A cross-sectional FRI was defined utilizing bone density relationships [3].

Results

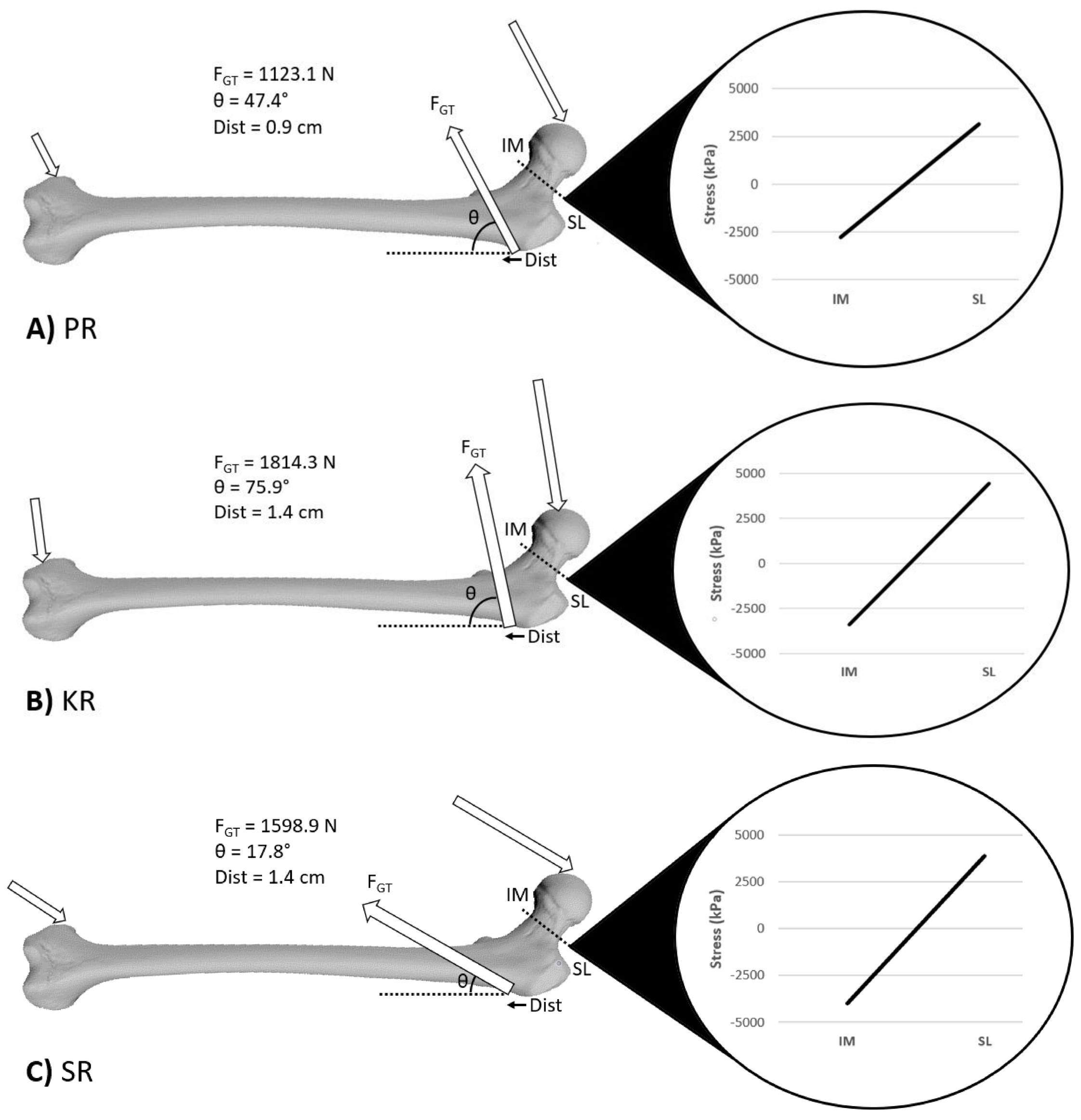

Figure 5: Stress generation in the superior-lateral (SL) and inferior-medial (IM) narrow neck during a) pelvis (PR), b) kneeling (KR), and c) squat release (SR). Compressive stresses are indicated as positive.

Pelvis release, which had lower resultant impact force, elicited lower femoral stresses and FRI (Figures 5 & 6) than FSP incorporating lateral motion (all p<0.01). Kneeling release loading was directed more perpendicular to the femoral shaft and elicited greater SL compressive stresses, and lower IM tensile stresses, than squat release (all p<0.05); however, FRI did not differ between kneeling and squat release (p=0.960).

Despite greater and more localized impact force in males (both p<0.01) than females, no differences in stresses or FRI (Figures 5 & 6) were observed (p>0.484). Secondary analysis revealed males had greater resistance to stress generation and yield stress than females (all p<0.05).

Greater force magnitudes were observed for higher-TSTT participants; however, these loads were applied peripherally from the greater trochanter (both p<0.01). Although no differences in force applied directly over the proximal femur were observed (p=0.578), low-TSTT participants had greater stresses and FRI (Figures 5 & 6) than high-TSTT due to differences in femur morphology (all p<0.05).

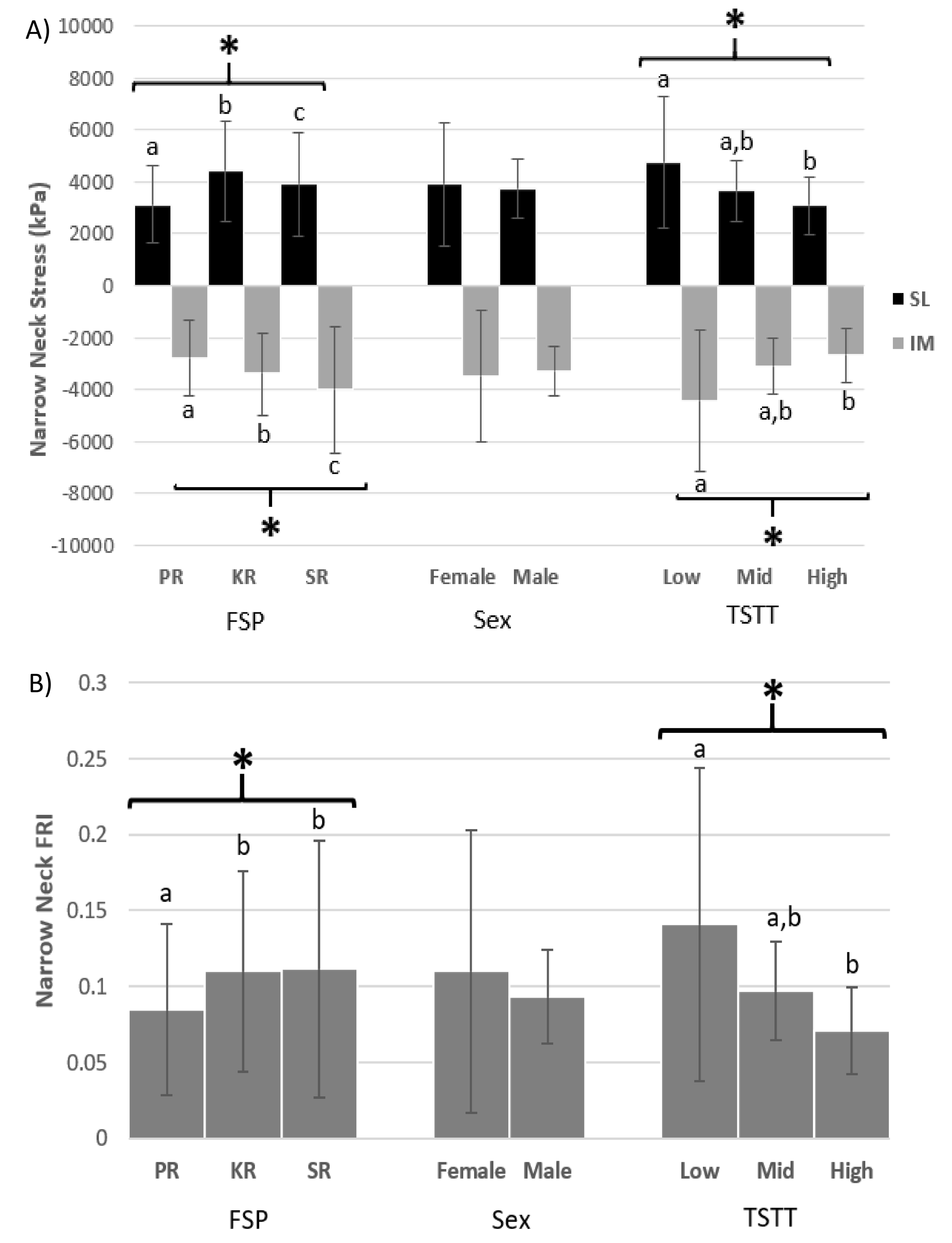

Figure 6: Influence of fall simulation paradigm, sex, and trochanteric soft tissue thickness on a) femoral neck stresses and b) fracture risk index (* indicates significant ANOVA main effects; letters refer to significant differences between groups based on Tukey's post hoc tests)

Discussion

- FSP, sex and TSTT had independent effects on metrics of impact severity and femur strength
  - Towards mirroring contributing factors, hip fracture risk analyses should consider both impact dynamics and underlying femur morphology
- The current results support epidemiological findings suggesting TSTT is a protective factor against hip fracture; however, sex differences in fracture risk are likely driven by age related changes in femur morphology not included in this analysis
- Based on the apparent importance to fracture risk, future work should aim to quantify the translation of skin surface pressure distributions to impact energy delivered to the proximal femur
- The framework developed in this study could be utilized in the design of impact mitigating protective devices

References

[1] Hayes et al. (1996). *Bone*, 18(1), S77-S86
[2] Mourtada et al. (1996). *JOrthRes*, 14(3), 483-492
[3] Morgan et al. (2001). *JBiomech*, 34, 569-577

Acknowledgments

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