Investigating the Likelihood of Pediatric Femur Fracture Due to Falls Through FEA

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Background

- Household falls are a common accidental injury mechanism as well as a common falsely reported cause in cases of abuse.
- In non-ambulatory children, femur fractures are more likely to be due to abuse.
- Clinicians must be able to delineate between abuse and accidental injuries.
- Currently little biomechanical evidence to distinguish accidental and non-accidental injuries.
- Previously, 12-month-old CRABI anthropomorphic test dummy (ATD) with a modified biofidelic femur was instrumented with two triaxial load cells and strain gauges to measure femoral loading
  - The biofidelic femur was based on infant CT images.
- ATD was used in simulations of:
  - Bed falls from a height of 61cm
  - Feet-first falls from heights of 69cm and 119cm
  - Both fall types conducted onto two impact surfaces: linoleum and padded carpet

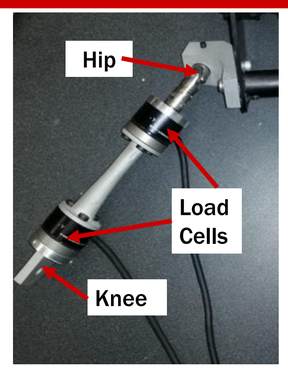

Figure 1. ATD Femur Assembly

Objective

- Use of an *in-silico* femur model
  - To evaluate stress and strain distribution in the femur due to bed and feet-first falls
  - To evaluate fracture potential

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Methods

- A post-mortem diagnostic CT scan of 11-month old child was used to derive a 10-node tetrahedron femur model meshed in 3-matic (Materialise, Ann Arbor MI). (341736 elements)
  - Applied a linear material model
- Analyzed in ANSYS Workbench (ANSYS Inc., USA) (Figure 2) using applied femur loads and constraints representing those in ATD fall experiments.
  - Subset of trials run. Recorded outcomes for each trial: Maximum principal stress and strain
  - ANOVA of factors (impact surface and fall dynamics, Table 1) for each fall type on peak stress and strain ($\alpha = 0.05$)
- Fracture Thresholds Considered
  - Tensile Yield Strain: 0.73% (Bayraktar, 2004)
  - Ultimate Tensile Strength: 100MPa (Vinz, 1969)
  - Ultimate Flexural Strength: 157.8MPa (Currey & Butler, 1975)

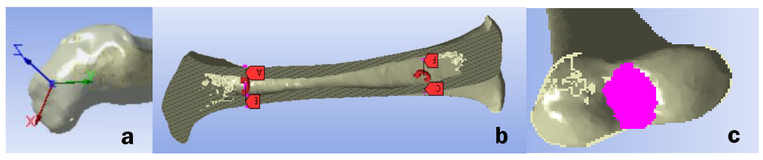

Figure 2. Applied constraints and loads in ANSYS Workbench.
- (a) Universal joint at the proximal end, no rotation about the longitudinal axis.
- (b) Application of ATD femur loading at corresponding load cell locations
- (c) Fixed displacement of the intercondylar (distal) region in pink

Fall Type	Factor 1	Factor 1 Levels	Factor 2	Factor 2 Levels
Bed Fall (n=12)	Impact Surface	Carpet	Fall Dynamic	Upper leg impacts first (B)
		Linoleum		Lower leg impacts first (A)
Feet-First Fall (n=12)	Impact Surface	Carpet	Fall Height	69cm
		Linoleum		119cm

Table 1. Factors and their levels for each fall type, bed and feet-first falls. Three trials were randomly selected for each interaction of factors for each fall type.

Results

Bed Fall

- Difference in peak stress and strain:
  - Fall Dynamic (A): Lower leg impacting first is greater than upper leg impacting first (p-value ≤ 0.026)
  - No difference due to impact surface
- Peak FE predicted outcomes for trials exceeding fracture thresholds associated with peak bending moments (14-23Nm) and compression

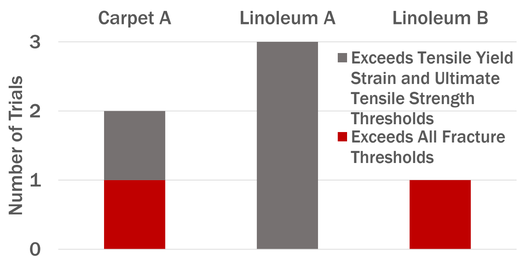

Figure 3. Bed fall trials exceeding fracture thresholds which include tensile yield strain, ultimate tensile and flexural strength thresholds. N=3 for all categories. Refer to Figure 4 for bed fall dynamic A and B.

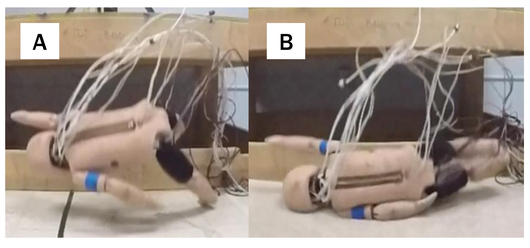

Figure 4. Bed fall dynamics where either the (A) lower or (B) upper leg impacted the ground first.

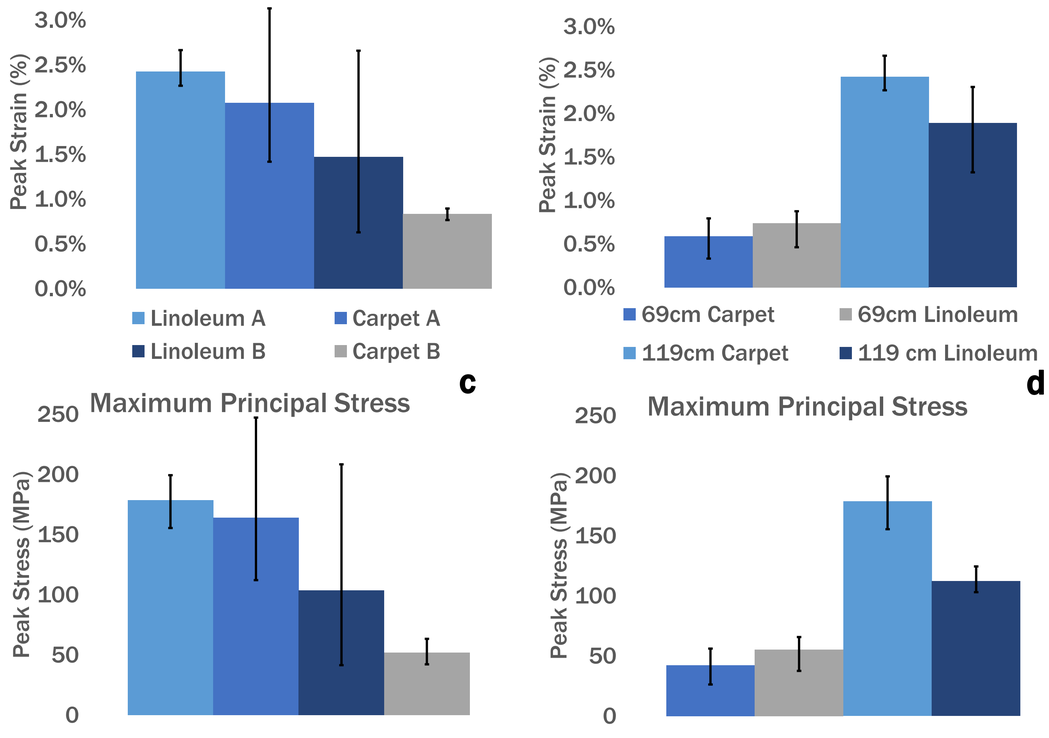

Figure 6. The peak maximum principal strain observed in the bed falls (a) and feet first falls (b) and peak maximum principal stress observed in bed falls (c) and feet first falls (d). Error bars represent the range of values observed. N=3 for all categories. Refer to Figure 4 for bed fall dynamic A and B.

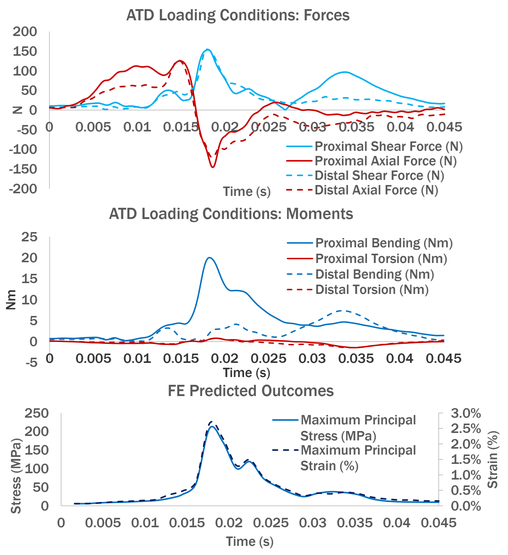

Figure 5. Representative time history of a bed fall onto linoleum of ATD femur force and moments and the FE predicted outcomes.

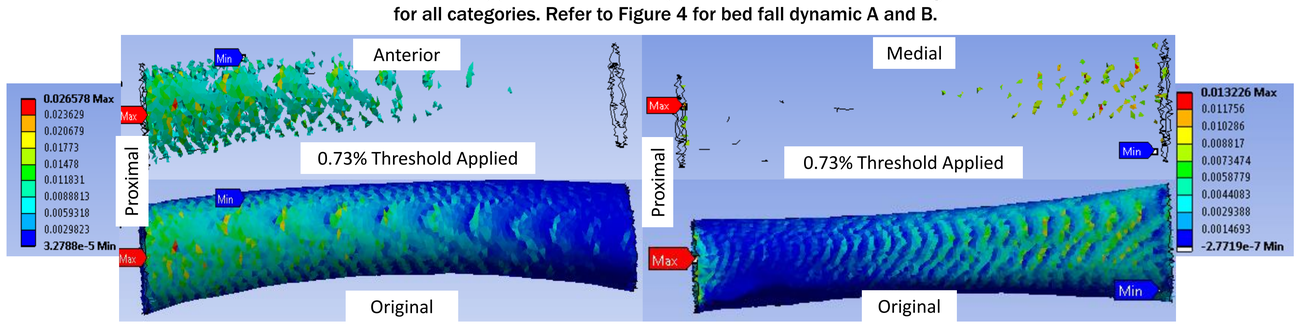

Figure 7. Maximum principal strain distribution of the evaluated diaphyseal region of the femur for a bed fall onto linoleum (left) and a 119cm feet-first fall onto linoleum (right) where all elements that exceed the tensile yield strain threshold are displayed. (Left) Medial View. (Right) Posterior View.

Feet-First Fall

- Difference in peak stress and strain for:
  - Fall Height: Greater for 119cm height (p-value = 0)
  - No difference due to impact surface
- No trials exceeded any fracture threshold
- Peak FE predicted outcomes associated with peak torsional or bending loads
  - Different dynamics resulted in different associated peak loading (bending vs torsion)

Figure 8. Feet-first fall dynamic associated with peak torsional loading

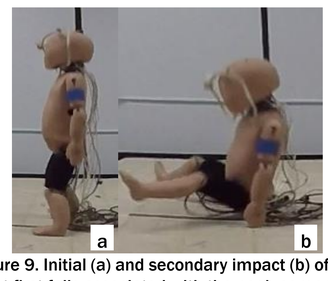

Figure 9. Initial (a) and secondary impact (b) of ATD in feet-first falls associated with the peak compressive and bending load, respectively.

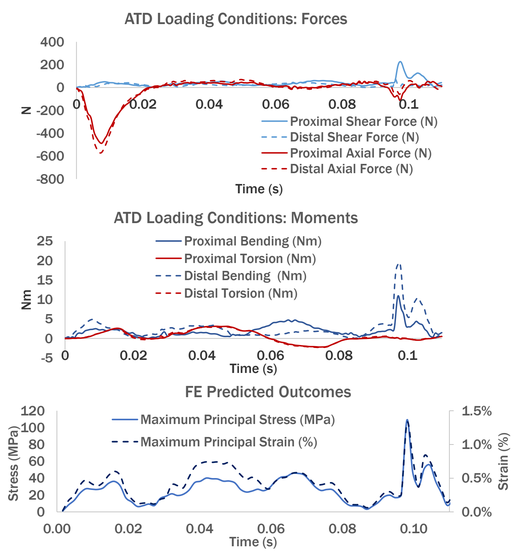

Figure 10. Representative time history of a 119cm feet-first fall onto linoleum of ATD femur force and moments and the FE predicted outcomes.

Limitations

- Material application: linear model and no consideration of effect of strain rate
  - Lack of studies defining pediatric mechanical properties, especially applied to FE models
- Stress-based thresholds are usually defined by density relationships
  - Elements exceeding thresholds are in higher density regions
- Lower resolution CT scan used to derive model
  - Can result in higher peak strains on surface of model due to partial volume effects

Conclusions

- Increased femur fracture potential represented by increased peak FE predicted outcomes are associated with:
  - Lower leg impacting first in bed falls
  - Falls from greater heights in feet-first falls
- 50% of evaluated bed falls had a potential for fracture
- No evaluated feet-first falls had a potential for fracture
- Future Work:
  - Addressing limitations of FE model and analysis
  - Improving understanding of representative dynamics of children falling through observation or more detailed clinical case histories
  - Expansion of model and analysis to other healthy, one year old subjects
- Clinical Relevance:
  - Bed falls may generate loads associated with femur fracture potential
  - Results indicate importance of detailing fall dynamics in histories when attempting to delineate between accidental and abusive diaphyseal femur fractures