

## ***Sex and Age Effects on Tibia Biomechanical Properties in Dynamic Four-Point Bending***

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### **Introduction:**

Globally, approximately 11 million pedestrian impacts each year result in injury or death. The lower extremity is the most frequently injured body region in pedestrian impacts, and these injuries often lead to long-term disability. To better understand lower extremity injury risk, biomechanical testing of the leg and tibia has previously been conducted. However, this work has mainly focused on males, despite females having a higher risk of sustaining lower extremity injuries in these loading events.

### **Objective:**

This study aimed to evaluate the effects of sex and age on biomechanical properties of the isolated human tibia in a diverse sample.

### **Methodology:**

Sixty-six tibiae from 35 females and 31 males with similar age distributions ( $p > 0.05$ ; females =  $68.8 \pm 3.4$  years; males =  $59.8 \pm 4.0$  years) were utilized. Tibial diaphyses (20–80% of bone length) were loaded to failure at 6 m/s in lateral-medial four-point bending to replicate vehicle bumper interaction in pedestrian impacts. Reaction forces were measured at each end of the bone. Proximal and distal moments were calculated as the product of reaction force and the distance from the axis of rotation to the nearest impact site. Peak bending moment at midshaft was further calculated as the maximum of the average proximal and distal moments. Strain at fracture was determined from an axial strain gage on the medial bone surface between impactor locations. Maximum deflection was normalized by span length.

### **Results:**

Males exhibited significantly greater peak moments than females ( $p = 0.001$ ). In the full sample, age demonstrated a weak but significant negative relationship with peak moment ( $p = 0.013$ ,  $R^2 = 9.3\%$ ); however, no significant age relationship was observed when males ( $p = 0.290$ ,  $R^2 = 3.9\%$ ) and females ( $p = 0.097$ ,  $R^2 = 8.1\%$ ) were analyzed separately. A mixed-effects model ( $p = 0.001$ ,  $R^2 = 21.2\%$ ) confirmed a significant effect of sex ( $p = 0.003$ ) on peak moment but not age ( $p = 0.051$ ).

Male tibiae had a significantly greater normalized deflection than female tibiae ( $p = 0.029$ ). Age was strongly and negatively associated with normalized deflection in the full sample ( $p < 0.0001$ ,  $R^2 = 42.2\%$ ), and for males ( $p < 0.0001$ ,  $R^2 = 50.8\%$ ) and females ( $p = 0.003$ ,  $R^2 = 27.6\%$ ) separately. A mixed-effects model ( $p < 0.0001$ ,  $R^2 = 44.1\%$ ) indicated that normalized deflection was significantly influenced by age ( $p < 0.0001$ ) but not sex ( $p = 0.173$ ).

No significant sex differences were observed for tensile strain at fracture ( $p = 0.133$ ). However, age had a significant negative relationship with tensile strain in the full sample and within each sex ( $p < 0.0001$ ). A mixed-effects model confirmed a significant effect of age ( $p < 0.0001$ ) but not sex on tensile strain.

**Conclusions:**

Although peak moment and normalized deflection account for differences in span length, sex differences were observed in both dependent variables, suggesting that additional factors such as bone geometry or material properties may contribute to these differences. The strong effect of age on deflection and strain suggests that age-related changes in material properties may also play a role global and local tibial deformation. Further investigation with larger sample sizes is needed to characterize the interacting effects of sex, age, and bone size across scales. Overall, this work advances understanding of tibial biomechanics and provides insight for improving pedestrian safety tools including anthropomorphic test devices and human body models.