

Associations between Vehicle Safety Systems and Pilon Fracture Severity are Revealed by Using a Novel Objective Quantitative Fracture Energy Metric

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Introduction: Intraarticular fractures of the distal tibia pilon are severe injuries associated with high rates of long-term disability and clinical complications. Motor vehicle crashes are a primary cause of these injuries, imparting high-energy axial compression that results in comminution of the tibia. Despite prior automotive safety research identifying ankle injury risk factors, the influence of crash mechanisms and vehicle occupant protection on distal tibia fracture severity and outcomes remain poorly defined. An objective quantitative computed tomography (CT)-derived fracture severity metric was recently developed to estimate the total fracture energy imparted to the bone, soft tissue, and cartilage during impact. This mechanically grounded measure captures elements of fracture severity not reflected in traditional classification systems and shows strong promise for advancing crash injury analysis and outcome prediction.

Objective: The goal of this study was to identify occupant, vehicle, and crash-related factors associated with severe pilon fractures using this novel fracture energy metric.

Methodology: The Crash Injury Research and Engineering Network (CIREN) is a large data collection program of crash occupants admitted to a participating Level-I trauma center. CIREN provides details of the crash kinematics, vehicle crashworthiness, occupant demographics, and injury CT images for statistical modeling purposes. After selecting frontal, non-rollover, non-ejection crashes with non-pregnant occupants 14 years and older seated in the front row, 62 pilon fractures were available. Fragment surface models were generated from CT (Materialise Mimics) and supplied to a validated custom MATLAB script (PMID: 39778442) to compute the fracture energy. A gamma-log linear model was used to determine how knee bolster airbag (KBAB) deployment, vehicle model year, belt use, age, sex, osteoporosis, BMI, delta-v, toe-panel intrusion, and injury mechanism were related to distal tibia fracture severity. The Corrected Akaike Information Criterion determined optimal subset of features and interactions for a best-fit model of the CIREN data. Model estimates were used to explain the individual effect of each predictor on distal tibia fracture energy with a significance level of 0.05.

Results: After controlling for age, sex, delta-v, belt use, mechanism, and osteoporosis in the best-fit model, fractures with KBAB deployment had a statistically significant 58% increase in fracture energy. This result coincides with previous studies that reported increased ankle fracture incidence with KBAB deployment. Female occupants were found to have a significantly lower fracture energy compared to males, and a significant interaction between age and sex was identified indicating a steeper age-related decline in male occupants. Given the age of these occupants (males: 44±16 [30-73 years], females: 44±17 [17-79 years]), this finding could indicate that females have already experienced an age-related decline in bone density that males typically experience later in life. Ultimately, the CIREN sampling yielded only a few (n=8) males, which limited the sex-based analysis.

Conclusions: The fracture severity metric explored successfully linked factors of vehicle crashworthiness to biomechanically relevant factors of injury severity not captured in existing categorical classification systems. These findings warrant further investigation into larger, representative datasets and causal statistical models to determine whether KBAB deployment contributes to disabling ankle fracture types.

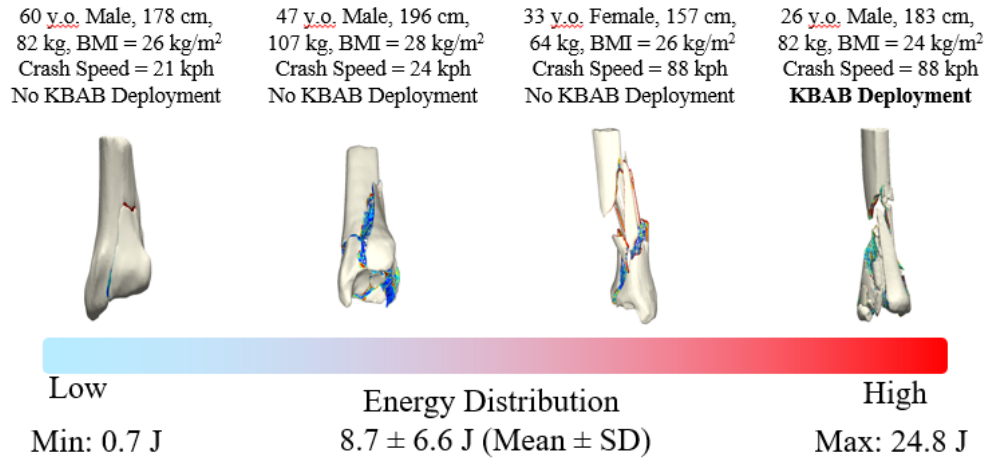


Figure 1. Distribution of fracture energy for pilon fractures in this sample from CIREN where the fracture liberated surface area is colored according to its density.