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

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ABSTRACT

Pilon fractures are a severe lower extremity injury sustained in motor vehicle crashes, characterized by high-axial loading that drives the talus into the tibial plafond and frequently results in poor long-term functional outcomes and post-traumatic osteoarthritis (PTOA). Despite advances in surgical management, long-term outcomes have remained largely unchanged, which highlights the need to identify modifiable upstream risk factors in the motor vehicle crash environment. The Abbreviated Injury Scale (AIS) is the predominant tool for crash injury severity analysis, and it classifies all closed pilon fractures uniformly as moderate (AIS 2) regardless of comminution or imparted energy and poorly predicts long-term functional outcomes. An existing fracture energy severity metric quantifies the acute mechanical energy delivered to bone during fracture, and has been linked to PTOA development, but has not previously been applied to crash injury analysis. This study represents the first multivariate application of the fracture energy metric to crash data, examining how occupant demographics, crash kinematics, and vehicle safety systems relate to pilon fracture severity. Fifty belted occupants with OTA Type B or Type C pilon fractures were identified through the Crash Injury Research and Engineering Network (CIREN) database. Fracture fragment surface models were generated from clinical CT and used to compute fracture energy severity through a custom MATLAB script. A gamma generalized linear model with a log link was fit using seven predictors: age, delta-v, knee bolster airbag (KBAB) deployment, fracture loading mechanism, biological sex, osteoporotic status, and BMI. KBAB deployment and pure axial compression loading were both significantly associated with higher fracture energy ($p = 0.011$ and $p = 0.002$), and age approached an inverse association ($p = 0.086$). These findings establish the fracture energy metric as a viable tool for crash injury analysis and suggest that certain vehicle safety system characteristics should warrant further investigation as modifiable factors influencing pilon fracture severity.

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INTRODUCTION

Lower extremity injuries account for a third of all injuries sustained in motor vehicle crashes (Dischinger et al. 2004). Fractures of the distal tibia are a severe lower extremity injury that have a reputationally poor prognosis due to the critical weight-bearing responsibility of the tibia. Poor clinical outcomes are reported in 20-50% of cases involving high energy fracture mechanisms, primarily motor vehicle crashes, often fracturing the critical weight-bearing articular surface known as the tibial plafond (Van den Berg et al. 2016). Fractures of the plafond are called pilon fractures, and the crash injury mechanism involves high-axial loading that drives the talus through the plafond, causing poor long-term functional outcomes like ankle range of motion below what is necessary for ambulation and chronic pain (Mair et al. 2021). Another prevalent and costly complication associated with pilon fractures is the development of post-traumatic osteoarthritis (PTOA) with clinical studies reporting PTOA in 25-74% of pilon fracture patients 1-2 years post-injury (Marsh et al. 2003). PTOA causes an immense societal and economic burden accounting for $12 billion USD annually in comprehensive costs (Brown et al. 2006). Despite advances in surgical management, long-term functional outcomes have remained largely unchanged, highlighting the need for research targeting modifiable upstream risk factors (McKinley et al. 2010).

Prior crash injury research has identified elevated ankle injury risk associated with a variety of factors, including occupant sex and knee bolster airbag (KBAB) deployment (Dischinger et al. 2016, Rudd 2009, Weaver et al. 2013, Patel et al. 2013); however, these studies predominantly characterized injury occurrence rather than severity relevant to long-term outcomes. A contributing factor to this gap in knowledge is the current systems of categorical representation of injury severity. The Abbreviated Injury Scale (AIS) codes are the most widely accepted measure of crash injury severity, and the most recent AIS dictionary labels closed distal tibia fractures as moderate (AIS 2) and open fractures as serious (AIS 3) (Gennarelli and Wodzin 2018). Despite the utility of AIS as a measure of the threat-to-life posed by an injury, it was found to not reliably predict the probable degree of functional limitations experienced 1-year post injury (MacKenzie et al. 1996). A novel fracture severity metric was recently developed that can address these limitations by quantifying the degree of acute injury severity not captured in existing categorical systems, called the fracture energy severity metric. The fracture energy is founded on an empirically validated relationship of the surface area created during fracture and that region's density to estimate the energy imparted to the hard and soft tissue structures (Beardsley et al. 2005). The fracture energy is a biomechanically relevant measure of acute mechanical damage that is associated with the cause of PTOA, and significant energy transmission into the plafond directly complicates the goals of surgical reduction and fixation. Furthermore, the fracture energy was found to reliably predict long-term functional outcomes and development of PTOA in distal tibia fractures (Thomas et al. 2010, Anderson et al. 2016, Dibbern et al. 2025). Ultimately, the fracture energy severity metric is a promising objective measure of injury severity with respect to the likely morbidity experienced by occupants following a pilon fracture. Despite the potential benefits of this novel fracture severity metric, no studies have yet implemented this methodology for crash injury analysis.

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This study represents the first application of the fracture energy severity metric in a multivariate crash injury analysis, utilizing the detailed case documentation available through the Crash Injury Research and Engineering Network (CIREN) to examine relationships between occupant demographics, crash kinematics, vehicle safety systems, and fracture energy in occupants sustaining pilon fractures. Through this novel characterization of injury severity, this study aims to identify crash-related risk factors associated with high-severity pilon fractures and generate insight to inform safety countermeasures targeting the reduction of long-term functional disability. Implementing the fracture energy severity metric will enable a robust analysis of the biomechanics of pilon fractures in CIREN to evaluate how vehicle safety restraints and occupant demographics influence tibial loading and fracture outcomes.

METHODS

Data Source

Pilon fracture cases caused by a motor vehicle crash were sampled from the CIREN program from 2005 to 2024 (Rudd and Lockerby 2018). CIREN is a large data collection program of crash occupants admitted to a participating Level-I trauma center. This database contains detailed medical and crash information for each occupant. Specifically, CIREN provides details of the crash kinematics, vehicle crashworthiness, occupant demographics, and injury computed tomography (CT) images necessary for the fracture energy computation.

Case Selection

For this study, pilon fractures were identified using the AIS 2015 and 2005/08 update dictionaries based on the corresponding CIREN case year. From this subset, certain selection criteria were implemented to mitigate potential confounding factors (Bangert et al. 2023). To ensure a consistent axial-loading injury mechanism across the cases, non-frontal, rollover, and ejection cases were excluded. Additionally, occupants who were pregnant or under 14 years old were excluded to account for differences in injury tolerance (Rupp et al. 2013). All chosen occupants must also have been front-row seated and belted to ensure similar available passive safety systems (Forman et al. 2019). Lastly, any cases where pilon fracture CT could not be retrieved or where CT contained interfering image artifacts were excluded to ensure consistent CT image-reading. After controlling for these selection criteria, 50 pilon fracture cases were available.

Fracture Fragment Surface Model Generation and Energy Computation

Materialise Mimics was used to create individual fracture fragment surface models for each fracture case from CT to later distinguish native from fracture-liberated bone. The entire tibia was first masked using intensity thresholding, then a proprietary adaptive watershed algorithm was utilized to mask the individual fracture fragments. Surface models of each fragment were then

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created using a proprietary meshing algorithm based on marching cubes, and the models were refined using Materialise 3-Matic. This was done to eliminate voids and overlapping geometries on the surfaces of each fragment. Finally, the models were remeshed to create approximately uniform triangles of edge length 0.5mm. 3D Slicer was then utilized to ensure the alignment of the CT images and fragment surface models so that they could be supplied to the MATLAB program. A custom MATLAB 2014a script was used to compute the fracture energy severity metric based on previous work done by Anderson et al. 2011 based on Eq. 1 below.

$$Energy\ (J) = \frac{1}{2} * SA_{liberated}(m^2) * \frac{HU}{10^{2.87}}^{\frac{1}{1.45}} \left(\frac{g}{m^3}\right) * \frac{12000}{1.98} \left(\frac{J*m}{g}\right) \quad (1)$$

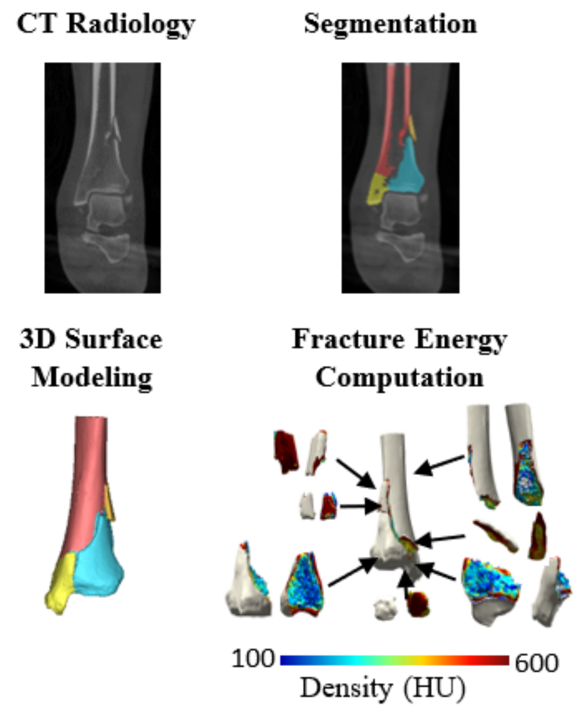

Figure 1. Fracture energy computation pipeline (from top left to bottom right) from CIREN CT radiology where 3D surface models are created for each fracture fragment and surfaces are classified as de novo or native bone. Hounsfield Unit (HU) values are visualized from 100 to 600 to help identify fracture lines along cortical bone.

Statistical Analysis and Interpretation

While linear regression is commonly used in crash injury analysis to examine a continuous outcome against a collection of predictor variables, it carries strict assumptions regarding the normality of the outcome variable, independence among predictors, and constant variance of residuals across the range of fitted values (Nimon et al. 2012). Alternate link functions offer a more flexible framework by accommodating non-normal outcome distributions tailored to the

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underlying data structure. In this study, the fracture energy followed a strictly positive and right-skewed distribution (Figure 2), which violated the normality assumption of a standard linear regression. This is due to fracture energy only being measured as positive values, and because most of the fractures occur at lower energy values with a few outlying higher-energy cases. To appropriately model this distribution and reduce systematic error, a gamma family with a log link function was specified (Ng et al. 2017).

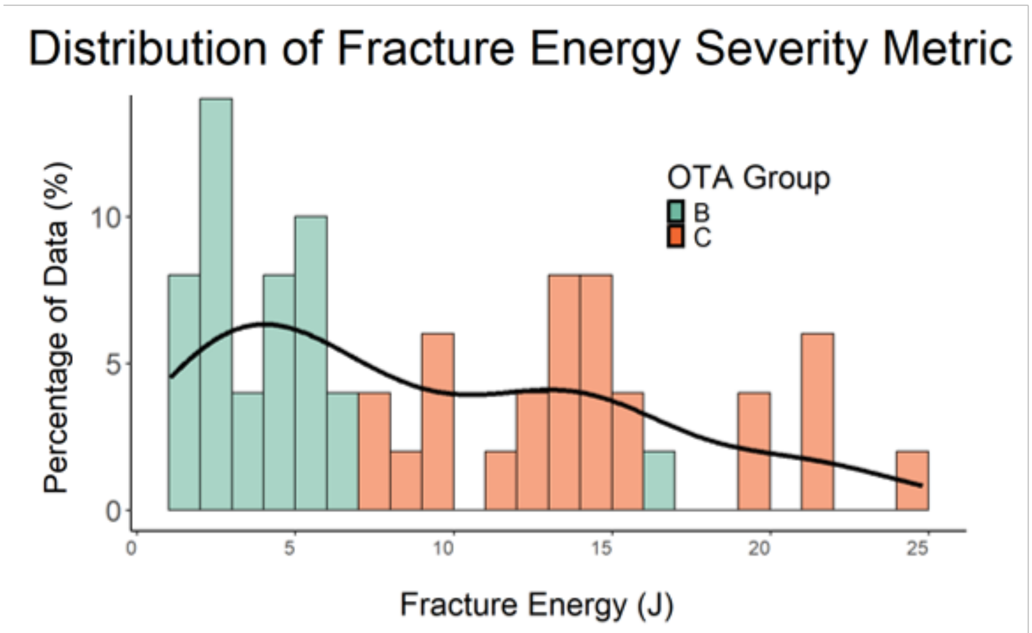

Figure 2. Distribution of the fracture energy severity metric from the sample of 50 CIREN pilon fractures.

Candidate predictors were selected based on their mechanistic relevance to pilon fracture loading as informed by existing crash biomechanics literature. The variables considered for inclusion were occupant age, biological sex, body mass index (BMI), crash severity as measured by crash speed (delta-v), knee bolster airbag (KBAB) deployment status, fracture loading mechanism, and osteoporotic bone status. Sex, KBAB deployment, fracture loading mechanism, and osteoporotic status were each encoded as categorical predictors. Sex was classified as male or female; KBAB deployment was classified as deployed or not deployed based on CIREN case documentation; fracture loading mechanism was classified as pure compression or non-pure compression, with non-pure compression containing fractures involving bending or rotational loading components in addition to axial compression; and osteoporotic status was classified as osteoporotic or non-osteoporotic according to documented patient medical history. Age, BMI, and delta-v were retained as continuous predictors. The sample was also restricted to partial-articular and complete-articular pilon fractures (OTA Type B or Type C pilon fractures), which yielded a final sample of 50 cases.

The final model was fit to the CIREN pilon fracture dataset using occupant age, delta-v, KBAB deployment, fracture loading mechanism, biological sex, osteoporotic status, and BMI. After model fitting, coefficient estimates were extracted for each predictor to characterize the

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direction and magnitude of their respective associations with fracture energy. Raw coefficient estimates must be exponentiated to give interpretable effect sizes, due to the gamma log-link model applying a logarithmic transformation to the outcome. For categorical predictors, each estimate reflects the proportional difference in fracture energy for a given level relative to its designated baseline. For continuous predictors, each estimate reflects the multiplicative change in fracture energy associated with a one-unit increase in that variable while holding all other predictors constant. Statistical significance was determined using an alpha level of 0.05, where predictors with a p-value below this threshold were considered to have a statistically significant association with fracture energy.

RESULTS

The final gamma log-link regression model was fit to a sample of 50 belted occupants sustaining OTA Type B or Type C pilon fractures identified through the CIREN database. The model included seven predictors: age, delta-v, KBAB deployment, fracture loading mechanism, biological sex, osteoporotic status, and BMI. Exponentiated coefficient estimates, representing multiplicative mean ratios relative to each predictor's baseline condition, are reported in Table 1. Two predictors reached statistical significance at the alpha level: KBAB deployment and fracture loading mechanism. Occupants in cases where the KBAB did not deploy demonstrated fracture energies that were on average 43% lower than occupants in cases where the KBAB deployed (mean ratio = 0.57, p = 0.011). Fractures characterized by a non-pure compression mechanism were associated with fracture energies that were approximately 48% lower than those resulting from pure compression loading (mean ratio = 0.52, p = 0.002).

Table 1. Gamma log-linear model estimates, errors, and mean ratios. Significant relationships are denoted by bold text indicating a p-value less than 0.05.

Predictor	Effect ± Error	Mean Ratio	P-Value
Intercept	**3.839 ± 0.778**	**46.488**	**<0.001**
Age	-0.011 ± 0.006	0.989	0.086
Delta-v	-0.005 ± 0.004	0.995	0.284
BMI	0.004 ± 0.014	1.004	0.789
KBABs Not Deployed	**-0.557 ± 0.210**	**0.573**	**0.011**
Rotational Mechanism	**-0.648 ± 0.199**	**0.523**	**0.002**
Female Occupant	-0.189 ± 0.226	0.827	0.406
Non-Osteoporotic	0.349 ± 0.341	1.416	0.312

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Occupant age appeared to have a borderline association with fracture energy, as it approached significance with a mean ratio of 0.989 per year, and a p-value of 0.086. This suggests a trend toward lower fracture energy with increasing age. The remaining predictors – delta-v, biological sex, osteoporotic status, and BMI – did not reach statistical significance ($p > 0.05$ for all). Female occupants showed fracture energies approximately 17% lower than male occupants on average (mean ratio = 0.83, $p = 0.406$), and non-osteoporotic occupants demonstrated fracture energies approximately 29% higher than osteoporotic occupants (mean ratio = 1.42, $p = 0.312$), though neither association was statistically distinguishable from chance given the available sample size. Delta-v and BMI showed negligible associations with fracture energy (mean ratio = 0.995, $p = 0.284$ and mean ratio = 1.004, $p = 0.789$, respectively).

DISCUSSION

This study represents the first application of the fracture energy severity metric to a multivariate crash injury analysis. The metric resolves gradations of injury severity within a single AIS code that have not been previously accessible in crash injury research. KBAB deployment and fracture loading mechanism along with the borderline age association suggest that fracture energy is sensitive to biomechanically meaningful variation among pilon fractures that existing categorical systems do not capture.

Fractures resulting from pure axial compression loading were associated with approximately 48% higher fracture energy than those involving bending or rotational components (mean ratio = 0.52, $p = 0.002$). This finding is consistent with the established pilon fracture mechanism, in which high-axial loading drives the talus directly into the tibial plafond and concentrates energy delivery onto the articular surface (Mair et al. 2021). When bending or rotational components are present, energy is partially dissipated through soft-tissue structures rather than transmitted fully into the bone. This statistically strong association validates the fracture energy metric and is clinically relevant as pure-compression injuries impart greater energy to the articular surface and complicate surgical procedures (Thomas et al. 2010, Anderson et al. 2016).

On average, occupants in cases where the KBAB deployed sustained fracture energies 43% higher than those in cases without deployment (mean ratio = 0.57, $p = 0.011$). This finding is consistent with prior work by Patel et al. (2013), who reported higher knee-thigh-hip fracture risk in vehicles with deployed knee airbags. One plausible explanation is that KBAB deployment in relation to occupant position involves unmeasured crash dynamics that alters the load path through the lower extremity in a manner that increases axial transmission into the tibial plafond. The present finding underscores that the relationship between knee bolster airbags and distal tibia injury severity requires further investigation rather than being treated as resolved by injury-occurrence studies.

Occupant age approached but did not reach significance (mean ratio = 0.989 per year, $p = 0.086$), with this trend suggesting lower fracture energy at older ages. This finding is opposite to

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what would be expected if bone fragility were the dominant driver and instead supports the interpretation that fracture energy relates to the mechanical energy imparted at the moment of injury rather than the structural capacity of the bone. This is supported by the null osteoporotic finding (mean ratio = 1.42, $p = 0.312$). The remaining null associations for delta-v, biological sex, and BMI reflect the limited power of the sample size of only 50 cases. They do not rule out these meaningful effects, but a larger sample would need to be analyzed to better understand these factors and their effects.

These findings demonstrate the value of an objective, continuous measure of acute injury severity. AIS classifications group all closed pilon fractures as moderate (AIS 2) regardless of differences in comminution, articular involvement, or imparted energy, despite plenty of evidence that long-term functional outcomes vary heavily for these types of injuries (MacKenzie et al. 1996). The fracture energy severity metric solves this issue by quantifying acute mechanical damage in a manner previously linked to PTOA and long-term function (Thomas et al. 2010, Anderson et al. 2016, Dibbern et al. 2025).

There are several limitations to be acknowledged with this study. The sample size of 50 cases limits statistical power, particularly for detecting modest effects across correlated predictors. KBAB deployment is also correlated with the generation of the vehicle and the configuration of the crash, and the present analysis cannot fully isolate the airbag effect from these confounders. Lastly, this study does not link the fracture energy findings to clinical outcomes reported in the CIREN cohort. Prior work has established the relationship between fracture energy and PTOA in clinical populations, confirming that this link in crash-injured occupants is an important next step. Future work should analyze a larger sample of CIREN cases as they accrue and should incorporate more granular vehicle and crash data to ultimately link fracture energy to reported functional outcomes.

CONCLUSIONS

This study is the first to apply the fracture energy severity metric to a multivariate crash injury analysis, demonstrating that this objective, continuous measure resolves biomechanically meaningful variation in pilon fracture severity that the categorical AIS framework does not capture. From the sample of 50 belted occupants with OTA Type B or Type C pilon fractures from the CIREN database, pure axial compression loading and KBAB deployment were both significantly associated with higher fracture energy. Occupant age showed a borderline inverse association. The KBAB finding aligns with prior evidence of elevated lower-extremity injury risk in vehicles where knee airbags deploy and shows the relationship between this safety system and distal tibia injury severity requires further investigation. These results establish the fracture energy severity metric as a viable tool for crash injury analysis and a foundation for future work that links acute mechanical damage to long-term functional outcomes and PTOA development, which ultimately drive the lasting burden of pilon fractures.

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