Do Females Have a Higher Risk of Suffering Distal Tibia Fractures in Frontal Car Crashes?

L. Garrett Bangert, Caitlyn J. Collins, Luke E. Riexinger

Abstract Lower leg injuries are increasingly common in motor vehicle crashes accounting for 32% of all AIS2+ injuries. Distal tibia fractures have disproportionately poor clinical outcomes and subsequently affect a patient's ability to perform daily walking activities. Previous studies have identified trends suggesting that females are at increased risk of lower leg injuries. Therefore, the objective of this study is to quantify the relationship between sex and distal tibia fractures. The Crash Investigation Sampling System (CISS) is a nationally representative sample of police-reported, passenger vehicle, tow-away crashes. Accounting for the CISS sampling scheme, a logistic model was constructed to estimate the likelihood of distal tibia fracture while controlling for the occupant sex, age, belt use, and delta-v. Unbelted occupants, crashes at higher delta-v, and occupants older than 55 years were at higher risk of distal tibia fracture. All injuries were caused by interaction between the toe panel or foot controls and the occupant's leg. An increased injury risk for females was found, but did not reach statistical significance due to small sample size. Given that this trend has been shown in a number of other studies, continued research into sex-related differences in injury risk with larger sample sizes is needed.

Keywords *Lower Extremity, Distal Tibia Fracture, Motor Vehicle Crash Epidemiology, Sex Differences*

I. INTRODUCTION

Lower leg injuries tend to have worse clinical outcomes than injuries at other anatomical regions with the same AIS severity rating due to the classification method of the AIS scale primarily focusing on the threat an injury has on a person's life [1]. Despite the comparatively lower fatality risk, lower leg injuries have been shown to exhibit poor clinical outcomes with many issues persisting one year after a crash [2]. Furthermore, lower leg injuries are increasingly prevalent, accounting for 32% of all non-minor, or AIS2+, injuries in motor vehicle crashes [3]. Distal tibia fractures are a particularly severe lower leg injury often resulting in post-traumatic osteoarthritis and long-term difficulty walking. Significant financial burdens for society due to hospital costs and the effect on a survivor's ability to return to work are linked to these debilitating outcomes [4]. Pilon fractures, a fracture of the articular surface of the distal tibia caused by a large energy forcing the talus into the plafond of the tibia, is one example of an injury caused by motor vehicle crashes which has high rates of healing complications, bone infections, and, in some cases, requires amputation [5]. Two other examples of distal tibia fractures with poor healing outcomes are medial and posterior malleolus fracture [6-7]. Extended, debilitating lower-leg injuries from automotive crashes are a burden to both vehicle occupants and society as a whole. Therefore, determining the risk factors that play a role in motor vehicle crash injuries of the distal tibia is critical for the identification of potential methods for reducing or mitigating such injuries and adverse long-term outcomes [8].

Increased use of seat belts with a chest and pelvis restraints and the increasing prevalence of airbags as well as improvements to these safety restraints has significantly reduced the risk of fatal injury in frontal crashes [9]. Knee bolster airbags are a safety measure which limit the forward movement of the knee and pelvis to reduce contact between the occupant and the front instrument panel which can mitigate injury outcomes [10]. Both seat belts and knee bolster airbags mitigate injuries by controlling occupant kinematics during a crash and redistributing the forces experienced by the lower leg into their respective contact points. This safety restraint has played a role in decreasing the risk of fatal crash outcomes and mitigating occupant injury outcomes and could play a critical role in the prevention of leg injuries [10-11].

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Occupant, vehicle, and environmental factors have been used to characterize crashes and relate them to injury outcomes [12]. Sex-related differences, in particular, are often understudied or inconclusive in motor vehicle crash injury research [8]. Some studies have found that shorter, older, and lighter female occupants in the right front seat are the most likely occupant type to suffer severe lower leg injuries while other studies have found that increasing occupant mass and BMI is directly related to a higher incidence of lower leg injuries [4][7-8]. Historically, there were fewer crashes with female occupants compared to males; a 3:1 ratio of male to female drivers involved in crashes in 2002 [13]. The financial burden caused by crashes involving male occupants has subsequently been found to be 2 times greater [14]. Although the total number of cases involving male occupants is higher than females, this gap is shrinking in recent years as driving exposure is increasingly more equitable [15-18]. Therefore, understanding sex-related differences in vehicular crash outcomes is increasingly important. Isolating injury to the lower leg, Forman et al. found that female adults had a significantly higher risk compared to male adults [18]. Other studies have found an increased prevalence of injuries in the lower extremities of female occupants compared with male counterparts [7-8]. The differences in lower leg injury prevalence between males and females have been attributed to differences in limb size and seating distance from the steering column. Females tend to sit closer to the steering wheel which could cause them to be more likely to collide with the vehicle interior [5][9]. It is also known that females have different injury tolerances than males due to biomechanical differences. For example, females on average have a lower bone mineral density than males which is then exacerbated by menopause resulting in higher fracture risk for females. Height is a factor known to vary by sex on average with males generally being taller than females. A study which looked at similarly sized occupants found that females still had a higher risk of lower leg injury [22]. These are only a few examples which have been proposed as contributors to the apparent increased injury incidence in female occupants. These findings suggest there may be a sex-related risk factor in lower leg injuries relevant for identify steps to further vehicle safety.

The relationship between the mechanism of injury in a motor vehicle crash is multifaceted and it is difficult to relate singular factors with injury outcomes. The relationships between lower leg injury severity and height, body mass index (BMI), age, and seat position have been studied as factors related to the vehicle occupant (Table 1, significant features in bold) [9-10][20]. The studies in Table 1 report generally that female, older, taller, and heavier occupants have an increased risk of suffering lower leg injuries. Vehicles made before 2009 and crashes with high delta-v and more than 2 cm of toe panel intrusion were also found to be associated with higher risk. While these factors appear to impact the relative injury risk in the lower leg, these studies often did not consider covariate independence in their models i.e., using height and weight or sex and height as independent variables in a logistic regression model. If the effect on the outcome due to one independent variable varies based on another independent variable, an assumption of a logistic regression model is violated [24].

Table I
Lower Leg Injury Factors

Author	Factors	Odds Ratio	Region	Dataset
Forman et al [18]	delta-v (kph)	**1.09 (1.07-1.11)**	Ankle AIS 2+ (including malleoli fractures)	NASS/CDS
	Female (vs. male)	**2.29 (1.48-3.53)**		
	Age (years)	**1.03 (1.02-1.03)**		
	Height (cm)	1.00 (0.98-1.02)		
	BMI (kg/m^2)	**1.07 (1.04-1.10)**		
	Model Year 2009+	0.65 (0.38-1.09)		
Forman et al [18]	delta-v (kph)	**1.08 (1.07-1.09)**	Leg AIS 2+ (including distal tibia fractures)	NASS/CDS
	Female (vs. male)	**3.80 (2.26-6.38)**		
	Age (years)	**1.01 (1.00-1.02)**		
	Height (cm)	**1.03 (1.00-1.06)**		
	BMI (kg/m^2)	**1.08 (1.04-1.13)**		
	Model Year 2009+	**0.40 (0.26-0.61)**		
Chong et al [20]	Female occupant	**Increased risk**	Foot and ankle fractures	CIREN
	Height	**Increased risk**		
	Age	No association		
	Weight	No association		
	BMI	No association		
Ye et al [19]	Toe pan intrusion > 2cm	**9.10 (1.82–45.42)**	Below knee	NASS/CDS
	Female occupant	**6.83 (1.56–29.93)**		
	Increased mass	**1.04 (1.02–1.06)**		
	Age	No association		
	Height	No association		
Ryb et al [25]	Age 61 - 70 vs. 16 - 30	1.30 (0.81–2.08)	Tibia fracture	CIREN
	BMI > 25	1.31 (0.66–1.23)		
	Driver (vs. RFP)	**1.61 (1.12–2.36)**		
	Male	0.80 (0.57–1.13)		
	delta-v > 60 vs. ≤ 30	**1.78 (1.15–2.77)**		

This study will seek to improve upon existing studies by ensuring independence among the predictor variables in the model as well as focus on distal tibia fractures in males vs females while considering seat-belt use and the presence of knee bolster airbags as factors affecting lower leg injury risk. The goal of this study is to determine the relationship between sex and distal tibia fractures due to the historically poor clinical outcomes and previous studies indicating that females suffer lower leg injuries disproportionately.

I. METHODS

A. Dataset

This study used the Crash Investigation Sampling System (CISS), an in-depth crash investigation dataset collected by NHTSA since 2017, as the primary data source for all features in this model. CISS data collection began in 2016 but the first full case year, with sampling weights available, was 2017. CISS is a nationally representative, probability sample of police reported passenger vehicle crashes where a vehicle was towed from the scene. CISS is the successor to the National Automotive Sampling System Crashworthiness Data System (NASS/CDS) and includes a number of updates to fit the contemporary vehicle safety technologies [26]. The CISS sampling scheme oversamples more severe crashes. As such, sampling weights account for this oversampling to provide a nationally representative crash sample [27]. Event data recorders (EDR) collect driver behaviour data before and after an impact or near-crash event making them a promising method for obtaining detailed crash data [28]. EDR data is becoming increasingly available in vehicles with more than 99% of all vehicles made in 2015 being equipped with an EDR and 57% of all vehicles on the road being equipped with an EDR [29]. EDR data is collected by the scene investigators in CISS if available [30]. The delta-v, a measure of the severity of a traffic collision was selected as a risk factor of interest as elevated delta-v is often associated with more severe injury outcomes [31].

B. Case Selection

Lower leg injuries most common in frontal area collisions, so only these crash types are included in the current study [32]. This also keeps the loading of the distal tibia similar for each selected case. Delta-v is an important metric for determining injury severity [31]. If the EDR delta-v was not recorded or was recorded as unknown, the WinSMASH computed delta-v was used when available [33]. Due to significantly different loading mechanisms on occupants in a rollover crash, only non-rollover crash cases were selected. Ejected occupants were excluded as they experience significantly different crash kinematics as well. Due to the small number of pregnant occupants (1.33% of female occupants) and the significant differences compared to non-pregnant females, pregnant occupants were excluded [34]. Children have significantly different injury tolerances compared to adults, therefore, only occupants at least 14 years-old were considered for this study [16-17]. Due to differences in passive safety systems between the front rows and back rows of a vehicle, only front seat occupants were included from this study. Since sex and height are not independent of each other, the sample design needed to control for height to ensure the robustness of the model [24]. To control for height, the data was stratified by selecting only occupants with a height below 175 cm, the 50th percentile male ATD height [37]. Mitigating the effects of height within our study by stratification was necessary to satisfy all assumptions of the logistic regression model as height would be a covariate, a factor outside of our model which affects the injury outcome. The 50th percentile male ATD height was selected due to its frequent use in vehicle regulatory tests and to enable cross-comparison with other studies. Finally, only cases with valid data for all modular features were considered. Table II shows the raw and weighted case counts for the vehicle-related selection criteria and the occupant-related selection criteria.

Table II
Selection Criteria

Case Selection Criteria	Vehicle Count		Vehicle Count Weighted	
All cases from 2017-2021	25,918		24,366,584	
Frontal area impact crashes	14,099		12,619,098	
Non-rollover crashes	13,121		11,952,709	
	Female Count	**Female Weighted**	**Male Count**	**Male Weighted**
Male or non-pregnant female	7,539	6,326,503	8,390	7,278,585
Non-ejected occupants	7,492	6,311,056	8,300	7,247,598
Occupants ≥ 14-years-old	6,854	5,777,432	7,701	6,769,905
Driver or right-front passenger	6,438	5,398,176	7,315	6,433,620
Occupants ≤ 175 cm	3,797	2,844,516	1,812	1,585,763
All valid data collections	1,557	963,671	597	446,452

C. Study Groups

The Abbreviated Injury Scale (AIS) codes in the CISS injury database were used to separate cases into two groups for a comparative analysis. The first group were occupants where an injury sustained was a distal tibia fracture which corresponds to AIS codes 854331.2, 854332.3, 854351.2, 854352.3, 854361.2, 854362.3, 854371.2, and 854372.3 [38]. The AIS codes for distal tibia fractures comes from the AIS 2015 codes which are currently used in CISS [39]. All other occupants did not sustain a distal tibia fracture including occupants without injuries. Using the sampling weights, this resulted in 446,344 male occupants without distal tibia fracture, 107 male occupants with distal tibia fracture, 962,062 female occupants without distal tibia fracture, and 1,609 female occupants with distal tibia fracture.

D. Injury Producing Component

The injury producing component (IPC) denotes the injury-causing collision partner of the vehicle occupant. This information is collected by CISS investigators for each injury in the crash. There can be multiple areas that attribute to an injury, but only the principal IPC was considered for this analysis. Correlating the IPC with injury type could provide further insight into the injury causation mechanisms of distal tibia fractures.

E. Logistic Regression

Using the survey library in R, a multivariate logistic regression was computed. Logistic regression is a type of regression analysis for predicting binary outcomes [24]. This method can be applied to determine an odds ratio (OR) of selected features from CISS in relation to the risk of distal tibia fracture. A logistic regression also outputs an intercept representing the log odds of distal tibia for the baseline scenario. This model predicts the risk of suffering a distal tibia fracture based on sex, age, longitudinal delta-v and belt use. A feature was required to have a p-value less than 0.05 to be considered to have a significant effect on distal tibia fracture risk. BMI, knee bolster airbag presence, and seat position were initially considered within this model, but were omitted after being found to not have a statistically significant effect on distal tibia fractures. In logistic regression, it is important to determine if any features within the model have an interaction effect. An interaction refers to a situation where the combined effect of two or more covariates is greater than the effect of each factor individually. All features in this model were determined to not have a significant interaction with any other covariate based on the p-value of their interaction.

II. RESULTS

Male occupants appeared to have a 9-fold lesser risk of distal tibia fracture but the results were not statistically significant. Occupants younger than 55 years were found to be 12 times less likely to suffer a distal tibia fracture (p=0.011), and belted occupants were at approximately a 2.7-fold decreased risk (p=0.019). There was an 8% increased risk per 1 kph increase in delta-v of the crash. This effect is significant as the mean longitudinal delta-v of distal tibia fracture crashes in this study was 50 kph, where an occupant would have 4-fold risk of injury compared to occupants in a crash with a delta-v of 0 kph (p<0.001, Fig.1). The intercept value in the model refers to a belted male occupant younger than 55 in a crash with a delta-v of 0 kph (Table III). Occupants that suffered a distal tibia fracture tended to be older (Fig. 2). Cases with distal tibia fractures also had a higher delta-v, with median delta-v for distal tibia fracture cases being 50 kph while non-tibia fracture cases had a median delta-v of 20 kph (Fig. 3).

TABLE III
Odds Ratios of Features

Risk Factor	Estimate ± Standard Error	P-value	OR [95% CI]
Age < 55 years	-2.52 ± 0.87	**0.011**	0.08 [0.01,0.44]
Male Occupant	-2.17 ± 1.19	0.088	0.11 [0.01,1.19]
delta-v increase by 1 kph	0.07 ± 0.01	**<0.001**	1.08 [1.06,1.09]
Belted Occupant	-0.98 ± 0.38	**0.019**	0.37 [0.18,0.78]
Intercept	-6.55 ± 0.69	-	-

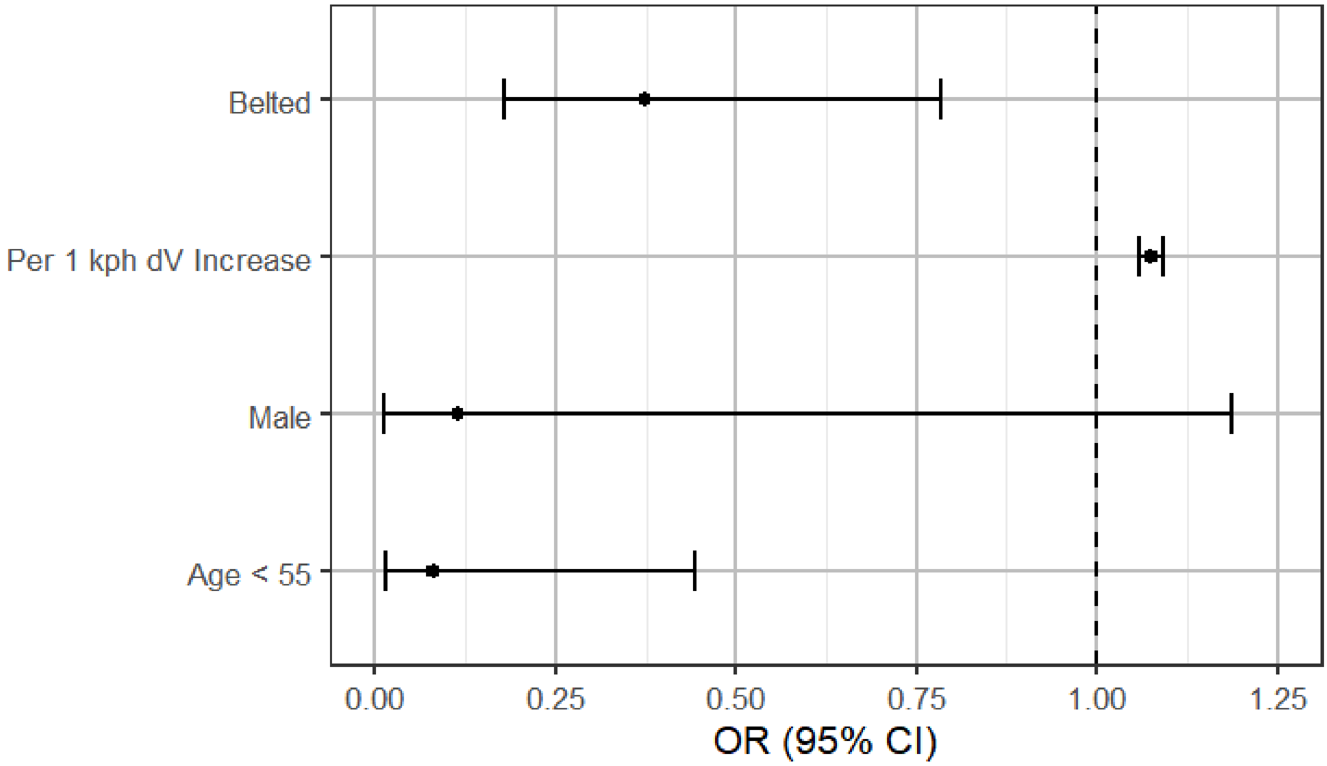

Fig. 1. Odds ratios and error bars for factors influencing the risk of distal tibia fracture

Impact with the toe panel and with the foot controls were found to be the primary IPC for every distal tibia fracture case in this study. There were 17 female drivers who suffered a distal tibia fracture, 7 of which were unbelted and 7 were without knee bolster airbags. Using sampling weights, 95% of unbelted female drivers with a distal tibia fracture had an IPC recorded as the toe panel while only 36% of belted female drivers had the toe panel as the IPC. The IPC of 90% of female drivers with knee bolster airbags was recorded as the toe panel while only 24% of female drivers without knee bolster airbags had the toe panel as the IPC. There were 107 weighted male drivers who suffered a distal tibia fracture and was unbelted in a vehicle without knee bolster airbags with an IPC recorded as the foot controls. There was only 1 sampled (unweighted) male occupant within our selection criteria who suffered a distal tibia fracture. No other cases were recorded within our selection criteria where a male occupant suffered a distal tibia fracture. There were 456 female right front passengers with a distal tibia fracture, 433 belted and 23 unbelted, in vehicles without knee bolster airbags with an IPC recorded as the toe panel.

III. Discussion

This study found a significant protective effect with seat belts, similar to past studies, found that seatbelts can reduce or mitigate severe and fatal injuries. Seat belts protect the occupant by controlling their forward motion with restraints across the hip and chest areas. While this does not target the lower leg area directly, preventing the occupant from sliding towards the instrument panel could reduce the load on the leg from the lower toe panel or pedals. Pattimore et al. also found the toe panel and pedals to be the most common causes of lower leg injuries [40]. All distal tibia fractures in this study were found to be caused by interactions with the toe panel or the foot controls, which the occupant was likely in contact with before the crash occurred. Analysing the IPC stratified by safety restraints provided insight into how the restraints interact with injury causation mechanisms. In the current study, the toe panel was the most common IPC for unbelted drivers. Despite not having a significant effect in the risk of distal tibia fracture, the knee bolster airbags are another safety restraint which primarily function by controlling occupant forward motion by contacting the knees and redistributing forces on the occupant. The IPC of drivers was most often the toe panel in vehicles with knee bolster airbags similar to the IPC of unbelted occupants. Categorizing IPC by delta-v could further identify relationships between distal tibia fractures and injury causation mechanisms as delta-v has been found to be closely correlated with injury severity [41]. The toe panel was frequently recorded as the IPC in crashes with a delta-v greater than 50 kph while the foot controls were primarily the IPC in slower delta-v crashes. This may indicate toe panel intrusion which has been found to be correlated with lower leg injuries. This finding might suggest that preventing interactions between the occupant's foot and the foot controls in lower speed crashes could improve distal tibia safety.

The current study found an increased risk of distal tibia fracture with increasing age. There has been varying results on how age affects tibia fracture where some studies found no effect or an inverse effect between age and tibia fracture while others found increasing age does correlate with increased risk of tibia fracture [18-21][25][42]. Note, the studies which found a direct relationship between age and tibia fracture used NASS/CDS as a data source which has a similar sampling scheme to CISS used in this study. In contrast, the studies that found no relationship between age and tibia fracture used CIREN. One limitation of CIREN is that it samples from level 1 trauma centres which skews the sample largely towards more severe crashes. The relationship between age and injury could be masked in higher severity crashes as occupants, regardless of demographic factors, more likely suffer many severe injuries. Another limitation is that CIREN lacks a method to correct for the sampling bias where NASS/CDS and CISS have case weights resulting in a population-based sample [25].

This analysis controlled for height to study the relationship between sex and distal tibia fracture only considering similarly sized occupants because sex and height are not independent and height is known to be related to the risk of lower leg injury [20]. Female occupants were found to be at a higher risk of tibia fracture although the result was not statistically significant. The lack of statistical significance in this study could be due to a lack of sampled cases with male distal tibia fractures. A limitation with CISS is that the sampling scheme could miss rare crash scenarios due to small sample size. CISS records data for approximately 4,000 out of the total 2,700,000 (<1%) police-reported crashes where at least one vehicle was towed per year, so it is possible that rarer situations are not sampled [43]. Another limitation with this study is the height stratification. The 50th percentile male Hybrid-III ATD does not necessarily represent the 50th percentile male height of the United States population. However, the stratification of the sample at the 50th percentile Hybrid-III ATD is consistent with much of the studies in the field.

Toe panel intrusion plays a large part in lower leg injuries [40] and is proportional to delta-v [44]. Intrusion is another factor which could be of interest in predicting distal tibia fracture risk but is related to delta-v. Therefore, both cannot be used in the same logistic regression, but future studies could determine which variable is preferred for predicting specific lower leg injury outcomes or further characterize injury outcomes using toe panel intrusion as an alternative feature. Another future direction could be to examine if the IPC affects the fracture type or injury severity and therefore the long-term outcomes. Finally, over time as more cases are recorded in CISS, the sample size relevant to this study will increase and future analysis could improve the relationship reported in this model between sex and distal tibia fracture.

IV. CONCLUSIONS

Older occupants, unbelted occupants, and higher delta-v are correlated with a higher risk of distal tibia fracture in motor vehicle crashes. The toe panel and pedals are the primary IPC of distal tibia fractures. There is a trend in the data suggesting that females may have a higher risk of distal tibia fracture after controlling other relevant factors, but more data is required to determine the relationship with statistical significance.

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I. APPENDIX

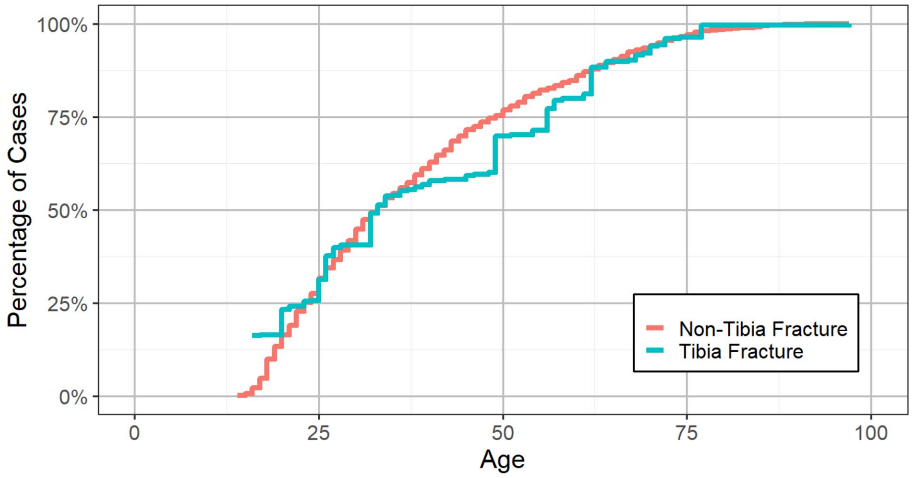

Fig. 2. Distribution of age and injury prevalence for occupants with and without tibia fracture.

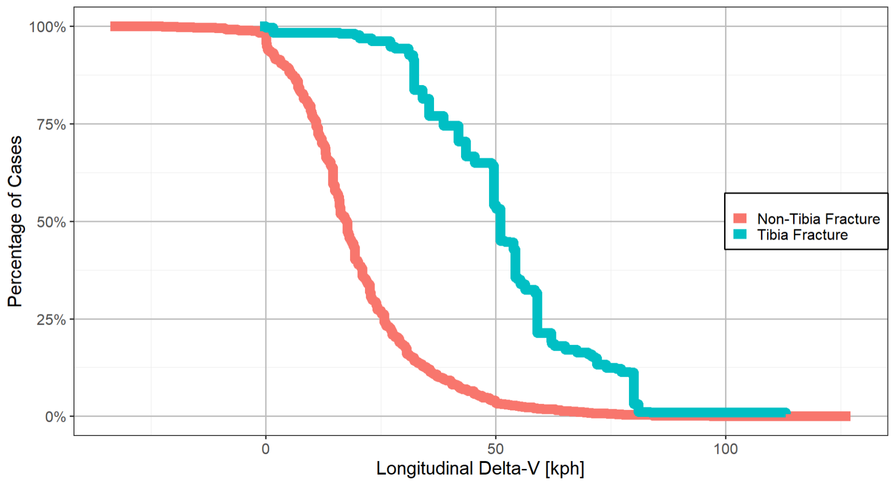

Fig. 3. Distribution of longitudinal delta-V and injury prevalence for occupants with and without tibia fracture.