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Incidence of fall-from-height injuries and predictive factors for severity

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Abstract

Context: The injuries caused by falls-from-height (FFH) are a significant public health concern. FFH is one of the most common causes of polytrauma. The injuries persist to be significant adverse events and a challenge regarding injury severity assessment to identify patients at high risk upon admission. Understanding the incidence and the factors that predict injury severity can help in developing effective intervention strategies. Artificial intelligence (AI) predictive models are emerging to assist in clinical assessment with challenges.

Objectives: This retrospective study investigated the incidence of FFH injuries utilizing conventional statistics and a predictive AI model to understand the fall-related injury profile and predictive factors.

Methods: A total of 124 patients who sustained injuries from FFHs were recruited for this retrospective study. These patients fell from a height of 15–30 feet and were admitted into a level II trauma center at the border of US-Mexica region. A chart review was performed to collect demographic information and other factors including Injury Severity Score (ISS), Glasgow Coma Scale (GCS), anatomic injury location, fall type (domestic falls vs. border wall falls), and comorbidities. Multiple variable statistical

analyses were analyzed to determine the correlation between variables and injury severity. A machine learning (ML) method, the multilayer perceptron neuron network (MPNN), was utilized to determine the importance of predictive factors leading to in-hospital mortality. The chi-square test or Fisher's exact test and Spearman correlate analysis were utilized for statistical analysis for categorical variables. A p value smaller than 0.05 was considered to be statistically different.

Results: Sixty-four (64/124, 51.6 %) patients sustained injuries from FFHs from a border wall or fence, whereas 60 (48.4 %) sustained injuries from FFHs at a domestic region including falls from roofs or scaffolds. Patients suffering from domestic falls had a higher ISS than border fence falls. The height of the falls was not significantly associated with injury severity, but rather the anatomic locations of injuries were associated with severity. Compared with border falls, domestic falls had more injuries to the head and chest and longer intensive care unit (ICU) stay. The MPNN showed that the factors leading to in-hospital mortality were chest injury followed by head injury and low GCS on admission.

Conclusions: Domestic vs. border FFHs yielded different injury patterns and injury severity. Patients of border falls sustained a lower ISS and more lower-extremity injuries, while domestic falls caused more head or chest injuries and low GCS on admission. MPNN analysis demonstrated that chest and head injuries with low GCS indicated a high risk of mortality from an FFH.

Keywords: artificial intelligence; border fall; domestic fall; injury; machine learning; multilayer perceptron neuron network

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Severity of injury from fall-from-height (FFH) is a serious concern for patient care. The fall-induced injuries can include fractures of the limb, spine, pelvic, brain injuries such as subdural hematomas and cranial trauma, chest injuries, and abdominal injuries, potentially leading to loss of independence or even death [1–3]. The severity of falls is a threat to patient health and quality of life, and is responsible for prolonged hospital stay, economic burden on the patient

and family as a result of the healthcare costs [4, 5]. Patients with a fall-related injury in the United States were reported to have hospital charges more than \$4,200 higher than patients who did not fall [6]. Fall-related injuries persist to be significant adverse events in acute hospitals and a challenge regarding implementing comprehensive fall-injury severity assessment tools to identify patients at high risk of falls upon admission [7–10].

Understanding the factors contributing to higher severity in fall-related injuries is crucial for an accurate diagnosis and timely intervention. By identifying the importance of factors, healthcare providers can adapt a better approach to an individual utilizing a predictive artificial intelligence (AI) model, potentially leading to more effective treatments and improved outcomes. This approach allows for earlier detection of issues, which can prevent injuries from escalating into more severe problems. It can also allocate resources and provide support appropriately. A comprehensive understanding of the severity factors benefits decision-making and the patients receiving care.

Injuries caused by FFHs at the US-Mexico border region included border-wall or fence falls, and jumps from a bridge, and these FFH injuries account for a significant amount of emergency admissions [11–16]. The previously reported studies on FFH injuries showed increased fallen height led to the worse outcomes and a higher rate of mortality [17–20]. These studies focused more on the difference in height and related injury severity rather than the difference in mechanism of fall types and related consequences or clinical outcomes. Moreover, only a few papers have addressed the difference of injury patterns and clinical outcomes between domestic falls and border falls [21]. Previous studies have evaluated the different types of injuries sustained from FFHs among undocumented immigrants crossing the border region, but they did not address similar domestic FFH injuries. The literature also lacks the study of the factors of FFHs leading to significant morbidity and mortality at trauma centers.

Falls from border fences or walls are of particular interest compared to domestic falls, such as falls from roofs, due to a combination of social, political, and unique situational factors. Falls from border fences or walls are often associated with high-risk, unauthorized border crossings. Border walls are constructed specifically to prevent crossing, they are usually taller, and they are designed to be difficult to climb. This can create a high risk of severe injury in case of a fall [22]. Domestic structures, while also hazardous but without deterrence measures, pose a different kind of risk. Falls from border walls can elicit humanitarian concerns, particularly the extreme risks that people are willing to take to cross borders, including the ethics of high barriers, the

physical risks that undocumented migrants face, and the balance between national security and humane treatment. In contrast, domestic falls generally do not prompt similar ethical or humanitarian discussions. Tracking and analyzing border falls and domestic falls provide data that can inform immigration and border security policies, which has important implications for policymakers and healthcare professionals to better understand and respond to the complex issues including injury severity and treatment [23].

The purpose of our retrospective study is to better understand the difference of FFH injury patterns and related injury severity between border falls and domestic falls. A machine learning (ML) predictive model approach was utilized to determine the importance of factors that can predict the severity of injury and in-hospital mortality.

Methods

Data sources

This retrospective study was performed at a level II trauma center in the Rio Grande Valley Sector near the US-Mexico border. An electronic chart review was performed, and data collection was performed by the treating physician and the allied health staffs. Patients admitted after a FFH to the trauma center between April 2014 and November 2022 were included in this study. Patients who sustained FFH injuries from 15–30 feet were included in the study. These patients were divided into two groups: (1) the “border falls” group, in which patients sustained a FFH injury while they attempted to cross the border via wall/fence or bridge; and (2) the “domestic falls” group, in which patients sustained FFH injuries unintentionally, such as falls from roofs, scaffolds, or trees. An ethics committee approval was obtained to conduct this retrospective study from the Western Institutional Review Board (South Texas Health System, 20216226).

Demographic information and collected variables

Factors collected on patient’s trauma registry included sex, age, Injury Severity Score (ISS), Glasgow Coma Scale (GCS) on admission, length of stay (LOS) in the hospital, intensive care unit (ICU) stay, days on mechanic ventilation, comorbidities (history of smoking, hypertension, diabetes mellitus, dyslipidemia, alcohol abuse/alcoholism), anatomic locations of the injury, fall height, fall types (border falls vs. domestic falls), and mortality in the hospital.

Statistical analysis

Descriptive statistical analysis outcomes are shown as mean $\pm$ standard deviation (SD), or percentage (%). Correlations between injury severity and predictive factors were analyzed. A chi-square test or Fisher's exact test and Spearman correlate analysis were utilized for categorical data analysis. A significance level of $p < 0.05$ was considered to be significantly different statistically. Statistical analysis was performed utilizing SPSS software (Version 28, IBM).

AI predictive model

A multilayer perceptron neural network (MPNN) was utilized to identify predictive factors and to stratify the importance of these factors associated with mortality (Figure 1). The cause-and-effect relationships were considered in selecting predictors. The dependent variable was in-hospital mortality. Predicting factors included sex, age, comorbidity, injury location, fall types (border fall vs. domestic fall), and other variables that had a significant correlation with injury severity.

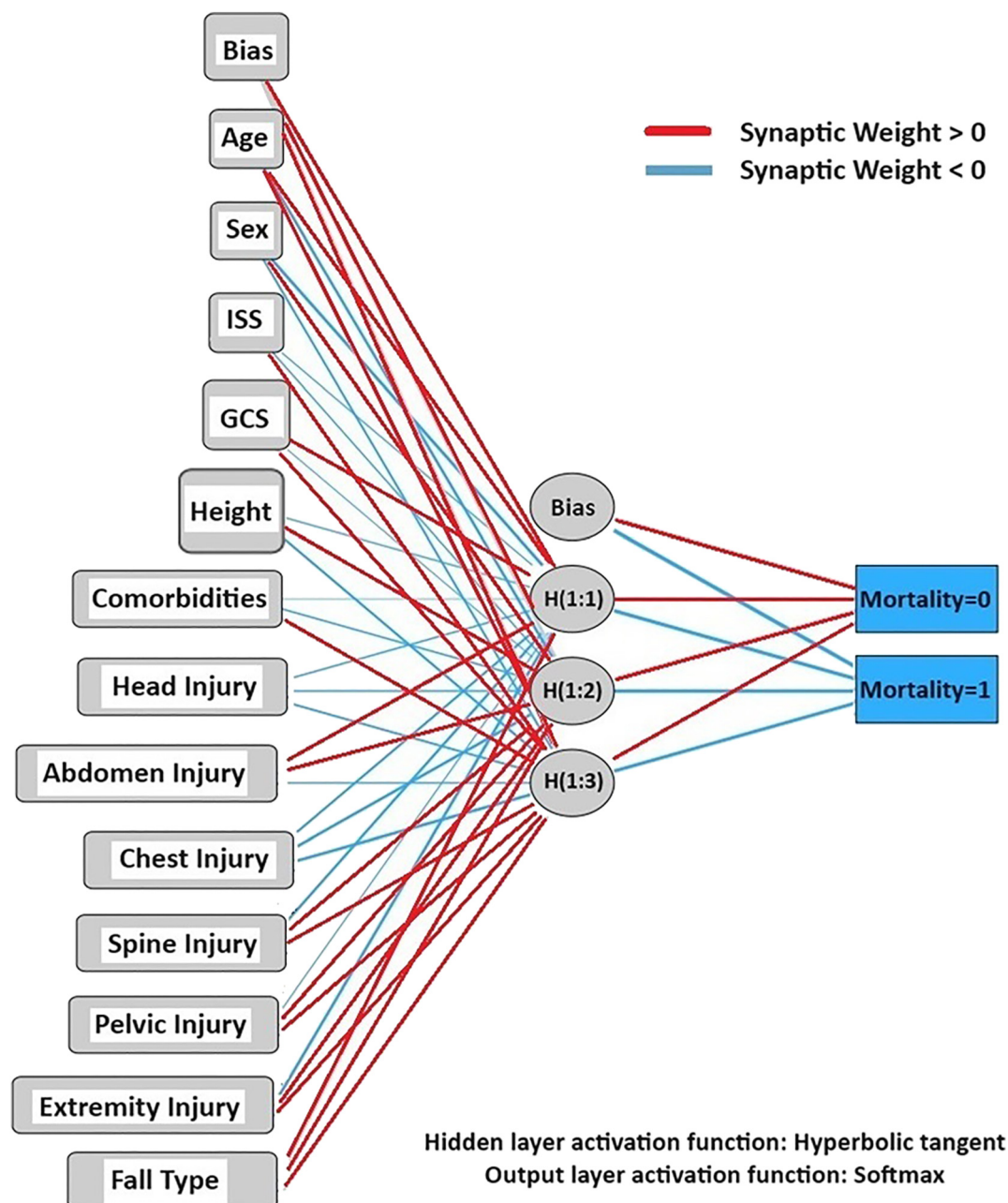


Figure 1: A multilayer perceptron neural network (MPNN) machine learning (ML) method for the prediction of factors contributing to in-hospital mortality.

A 70:30 training-testing was utilized to split the dataset partition. The MPNN analysis structure included an architecture with one hidden layer of a maximum of 50 units utilizing an automatic architecture selection function. Each hidden unit is a function of the weighted sum of the inputs. An automatic batch method was selected for the training type, with a scaled conjugate gradient utilized for the optimization algorithm. The initial learning rate was 0.4. The activation function in the hidden layer was the hyperbolic tangent. In the output layer, the dependent variable was the in-hospital mortality, and the activation function was Softmax. The loss/error function was cross-entropy. The importance of predictive variables was calculated based on a sensitivity analysis, which computed the importance of each predictor in the neural network (Figure 1) [24]. MPNN analysis was performed utilizing SPSS software (Version 28, IBM).

Results

Demographics

During the study period, among 124 patients, 64 patients (51.6 %) sustained FFH injury in the border fall group, whereas in the domestic group, 60 (48.4 %) patients sustained FFH injuries. The average age of the patients was 36.2 ± 13.4 years (mean $\pm$ SD) (range, 16–68 years), and most patients were males (77.4 %; 96 males and 28 females). The average ISS was 10.3 ± 7.7 (range, 1–68), and patients spent an average of 6.7 ± 5.2 days hospitalized (range, 1–31 days). The average fall height of both groups was 19.86 ± 4.6 feet (range, 15–30 feet).

In the domestic group, the most mechanisms of FFH injury were the falls from worksite such as scaffold and other (n=21, 35.0 %), followed by the falls from ladders (17, 28.3 %), followed by roofs (10, 16.7 %), running (2, 3.3 %) and trees (10, 16.7 %). And three patients died of falls from a ladder, roof, and work, respectively. In the border fall group, the mechanisms of falls were falls from wall/fence (45, 70.3 %), falls from bridge (13, 20.3 %), and falls from running during fleeing (6, 9.4 %).

In the domestic fall group, more male patients sustained injuries than female patients, whereas in the border fall group, more female patients sustained injury than male patients ($p < 0.001$, Table 1). The average age of border fall patients was younger than domestic falls ($p = 0.002$) (Table 1). The proportion of comorbidities of the border group was lower than that of the domestic group, including hypertension (7.8 % vs. 33.9 %, $p = 0.004$), diabetes mellitus (0.0 % vs. 16.9 %, $p = 0.004$), and fewer with alcoholism (12.5 % vs. 45.8 %, $p < 0.001$) (Table 2).

Table 1: Demographics of border fence falls vs. domestic falls.

Variable	Domestic fall (n=60)	Border fall (n=64)	p-Value
Age	40.0 $\pm$ 15.6	32.6 $\pm$ 9.9	0.02^a
Gender			
Male	58 (60.4 %)	38 (39.6 %)	<0.001^b
Female	2 (7.1 %)	26 (92.9 %)	
LOS (days)	6.5 $\pm$ 5.7	6.8 $\pm$ 4.7	0.071 ^a
ICU LOS	3.28 $\pm$ 4.1	1.6 $\pm$ 3.4	<0.001^a
Mechanic ventilation			
No	52 (45.2 %)	63 (54.8 %)	0.015^c
Yes	8 (6.5 %)	1 (0.8 %)	
Vent days	0.7 $\pm$ 2.3	0.1 $\pm$ 1.0	0.013^a
ISS	12.4 $\pm$ 8.7	8.3 $\pm$ 6.0	0.003^a
GCS on admission	14.1 $\pm$ 3.0	14.9 $\pm$ 1.0	0.062 ^a
Height, feet	18.1 $\pm$ 3.9	21.5 $\pm$ 4.6	<0.001^a
Mortality	3 (2.4 %)	0 (0.0 %)	0.11 ^c

^aMann-Whitney U test. ^bPearson's chi-square test. ^cChi-square Fisher's exact test. GCS, glasgow coma scale; ICU, intensive care unit; ISS, injury severity score; LOS, length of stay; Vent, ventilator. The bold values indicate the statistical significance with p value smaller than 0.05.

Table 2: Comorbidities between the two types of falls.

		Fall type		p-Value
		Domestic	Border	
HTN	No	39 (39.8 %)	59 (60.2 %)	<0.001^a
	Yes	20 (80.0 %)	5 (20.0 %)	
DM	No	49 (43.4 %)	64 (56.6 %)	<0.001^a
	Yes	10 (100.0 %)	0 (0.0 %)	
HLD	No	53 (45.7 %)	63 (54.3 %)	0.045^a
	Yes	6 (85.7 %)	1 (14.3 %)	
Asthma	No	58 (47.9 %)	63 (52.1 %)	0.731 ^a
	Yes	1 (50.0 %)	1 (50.0 %)	
Alcoholism ^b	No	32 (26.0 %)	56 (45.5 %)	<0.001^a
	Yes	27 (22.0 %)	8 (6.5 %)	
CVA	No	59 (48.4 %)	63 (51.6 %)	0.52 ^a
	Yes	0 (0.0 %)	1 (100.0 %)	
GERD	No	57 (47.5 %)	63 (52.5 %)	0.469 ^a
	Yes	2 (66.7 %)	1 (33.3 %)	
TB	No	59 (49.2 %)	61 (50.8 %)	0.256 ^a
	Yes	0 (0.0 %)	2 (100.0 %)	
IVDA	No	56 (47.1 %)	63 (52.9 %)	0.279 ^a
	Yes	3 (75.0 %)	1 (25.0 %)	

^aChi-square Fisher's exact test. CVA, cerebrovascular accident; DM, diabetes mellitus; GERD, gastroesophageal reflux disease; HLD, hyperlipidemia; HTN, hypertension; IVDA, intravenous drug abuse; TB, tuberculosis. ^bAlcoholism is defined as the continued drinking of alcohol despite it causing problems. Alcoholism was diagnosed utilizing International Classification of Diseases, Tenth Revision (ICD-10) codes for chronic alcoholism. The bold values indicate the statistical significance with p value smaller than 0.05.

Although the patients of border falls fell from a significantly higher height than domestic patients on average (21.5 ± 4.6 vs. 18.1 ± 3.8 , $p < 0.001$, Table 1), their ISS was lower than the patients of domestic falls (8.3 ± 6.0 vs. 12.4 ± 8.7 , $p = 0.003$). The

Table 3: Comparison of injury locations by fall type.

		Fall type		p-Value
		Domestic	Border	
Head injury	No	44 (41.5 %)	62 (58.5 %)	<0.001^a
	Yes	16 (88.9 %)	2 (11.2 %)	
Chest	No	44 (41.9 %)	61 (58.1 %)	<0.001^a
	Yes	16 (84.2 %)	3 (15.8 %)	
Abdomen	No	56 (46.7 %)	64 (53.3 %)	0.036^a
	Yes	4 (100.0 %)	0 (0.0 %)	
Spine	No	39 (48.8 %)	41 (51.3 %)	0.913 ^b
	Yes	21 (47.7 %)	23 (52.3 %)	
Pelvic	No	54 (47.7 %)	60 (52.6 %)	0.443 ^a
	Yes	6 (60.0 %)	4 (40.0 %)	
Extremity	No	35 (67.3 %)	17 (32.7 %)	<0.001^b
	Yes	25 (37.4 %)	47 (65.3 %)	

^aFisher's exact test. ^bPearson's test. The bold values indicate the statistical significance with p value smaller than 0.05.

Table 4: Comparison of lower-limb injury locations by fall type.

		Fall type		p-Value
		Border	Domestic	
Femur	No	63 (50.8 %)	57 (46.0 %)	0.353 ^a
	Yes	1 (88.9 %)	3 (11.2 %)	
Knee	No	63 (50.8 %)	60 (48.4 %)	0.516 ^a
	Yes	1 (0.8 %)	0 (0.0 %)	
Tibia	No	40 (32.3 %)	51 (41.1 %)	0.005^b
	Yes	24 (19.4 %)	9 (7.3 %)	
Fibula	No	42 (33.9 %)	53 (42.7 %)	0.003^b
	Yes	22 (17.7 %)	7 (5.6 %)	
Ankle	No	38 (47.7 %)	51 (52.6 %)	<0.001^a
	Yes	26 (60.0 %)	6 (40.0 %)	
Foot	No	62 (50.0 %)	58 (46.8 %)	0.666 ^b
	Yes	2 (1.6 %)	2 (1.6 %)	

^aFisher's exact test. ^bPearson's test. The bold values indicate the statistical significance with p value smaller than 0.05.

length of ICU stay was less in border fall patients than domestic patients (1.6 ± 3.4 vs. 3.28 ± 4.1 days, $p < 0.001$), and fewer border fall patients were put on mechanical ventilation (0.8 % vs. 6.5 %, $p = 0.013$) than domestic fall patients, with a shorter time of ventilation (0.7 ± 2.3 vs. 0.1 ± 1.0 days, $p = 0.013$). There was not an in-hospital death case in the border fall group, compared with three deaths in the domestic fall group, but there was not a statistical difference between two groups ($p = 0.11$).

The rate of the head injury was lower in the border fall group than the domestic fall group ($p = 0.004$). The rates of facial injuries ($p = 0.03$) and chest injuries ($p = 0.007$) were also lower in the border fall group than the domestic fall group. The rates of extremity injuries were higher in the border fall group ($p = 0.003$) (Table 3), particularly rates of the leg and ankle injuries including fractures ($p < 0.005$) (Table 4). The

rate of abdominal injuries was also lower in the border fall group ($p = 0.036$) than in the domestic fall group. There was not a statistical difference regarding pelvic injuries between the two groups ($p = 0.44$) or spine injury ($p = 0.913$).

AI predictive model and ML analysis outcomes

MPNN analysis ranked the strongest predictors for in-hospital mortality to be chest injury, then head injury, followed by GCS on admission, extremity injury, and abdomen injury, followed by other predictors that were not as strong (Figure 2).

Discussion

Falls have been consistently ranked as the second main cause of unintentional injury deaths worldwide. A fall is defined as “an event which results in a person coming to rest inadvertently on the ground or floor or other lower level” by the World Health Organization (WHO) (2021) [25]. A fall can happen from an elevated height or on flat ground, often leading to potential injury.

The injuries caused by an FFH persist to be significant adverse events and a challenge regarding injury severity assessment to identify patients at high risk on admission. Understanding the incidence and the factors that predict injury severity can help in developing effective intervention strategies to save lives. Our study demonstrated that the MPNN algorithm predicted the factors with stratified importance leading to higher severity or mortality with consideration of fall height, fall mechanisms (border fence vs. domestic falls), anatomical injury location, and demographics.

In this cohort of patients sustained from FFH injuries, the border fall group showed a younger age, fewer comorbidities, and a lower ISS on admission than the domestic group. Patients of domestic falls sustained more head and chest injuries, whereas border fall patients sustained more leg and ankle fractures. The injury patterns of border falls are consistent with the deliberate and possibly more falling posture-controlled nature with the leg landing first, whereas the domestic falls are consistent with unintentional or accidental nature with head or trunk landing posture [14]. Although there was not a statistical difference of in-hospital mortality rates between domestic and border fall groups, ICU stay was less in border fall than domestic fall patients.

The literature has reported that undocumented immigrants crossing the US-Mexico border frequently sustained musculoskeletal injuries, predominantly lower-limb injuries including fractures from FFHs [11–16, 26, 27]. While domestic

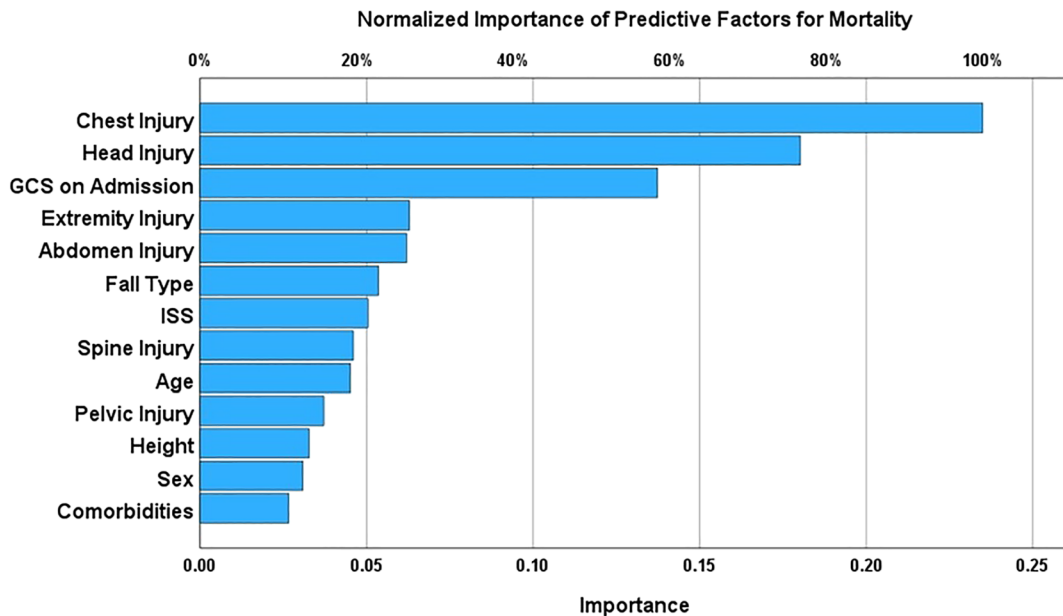


Figure 2: Normalized importance of independent factors related to in-hospital mortality is stratified showing the strongest predictive factors to be chest injury and head injury followed by GCS on admission.

falls have many different mechanisms with varying outcomes [17–30]. According to the WHO, falls are the second leading cause of unintentional injury deaths worldwide. A total of 37.3 million falls occur globally each year that are severe enough to require medical attention with reported deaths of over 660,000 adults and almost 30,000 children [25, 31]. There are no previous publications to address the fall-height, falling types (border fall vs. domestic fall), anatomic injury location, and their relation to injury severity, possibly due to the complex characteristics of injuries and multiple variables in datasets leading to sophisticated analysis required upon utilizing traditional statistical analysis. The AI and ML methods are emerging and have the potential to capture underlying trends and patterns that are otherwise impossible with traditional statistics approaches [32], thus to assist in clinical diagnosis [33].

In this study, we select the MPNN, a forward artificial neural network with stacked multiple layers of perceptron to build a predictive model to understand the importance of factors associated with injury severity. MPNN is one of the most utilized neural network architectures for building predictive AI models. MPNN has been utilized in many medical and orthopedic research [24, 34–39]. It has been utilized in clinical quality improvement projects and emergency care to reduce complications and costs [32, 40]. It produces approximate solutions for complex problems to better understand the correlation strength between multiple variables [40, 41], whereas traditional bivariate correlation analysis only determines the correlation strength between two variables. In

this study, we utilized MPNN to understand the critical mechanical factors leading to in-hospital mortality considering demographic information, comorbidities, fall height, fall location, injury location, and other clinical measurement. MPNN analysis ranked the strongest predictors for in-hospital mortality as chest injury and head injury, followed by GCS on admission, as predictors, suggesting that ICU care was required, as shown in our clinical interventions.

The predictive AI model may assist and improve the diagnosis on admission and treatment protocols for this cohort of FFH patients occurred at the border or domestic sites. In domestic falls, severe injuries to the head and chest were more common than the other anatomic locations. In border falls, the incident rate of extremity injuries was significantly higher than other anatomic locations. The tibia, fibula, and ankle injury rate was significantly higher in border falls than domestic falls (Table 4). It has been believed that border falls are intentional and more prepared with feet landing on the ground [14], whereas domestic falls are typically accidental and less prepared for controlled falling posture [21, 28, 29]. A theory has thus been proposed that the border falls from fence, wall, or bridge yield an axial load and vertical deceleration, which are forces that predominantly impact the musculoskeletal system, particularly the lower-extremity joints as evidenced by more tibia, ankle, calcaneus fracture, and joint injuries found in the border fall patients. Similar observations have been reported previously [21, 28]. Overall, we observed that border fall patients had less injury severity than domestic fall patients, as evidenced by a significantly lower ISS on

admission, and fewer border fall patients were admitted to the ICU among the border fall group. Other contributing factors can be that border fall patients were younger with fewer comorbidities, leading to less injury severity.

This study demonstrated that domestic FFHs yielded a higher ISS, longer ICU stay and longer mechanical ventilation than border falls. Overall injury severity was also higher in three death cases in the hospital. These three patients who died of domestic FFHs were older than the survivors (54.7 ± 6.1 vs. 35.7 ± 13.3 years, $p=0.023$), and had an ISS higher than survivors (36.3 ± 2.9 vs. 9.6 ± 6.5 , $p=0.01$), with a significantly lower GCS on admission (4.7 ± 2.9 vs., $p=0.026$). These three patients suffered from more multiple injuries than survivors, including brain injury ($p=0.002$), chest injuries ($p=0.003$), spine injuries ($p=0.043$), and fewer extremity injuries ($p=0.039$), suggesting that anatomic-injury locations are critical factors for mortality.

The impact of a fall depends on several factors beyond height alone, including body orientation, surface type, and the body's biomechanics at the time of ground impact. Studies have shown that falls from as low as 10 feet (approximately 3 m) can be fatal, depending on these variables [42]. Landing head first, for instance, can be far more dangerous than landing feet first. Falling onto a hard surface (like concrete) increases the likelihood of fatal injuries, whereas softer surfaces (grass, sand) can sometimes cushion the impact. What breaks the fall or absorbs some energy can make a difference. Encountering obstacles that slow the descent can reduce injury [43–45].

The type of ground surface and surroundings of falls are critical for injury but unknown in our study, making it one of its limitations. Among the other limitations are the sample size, which is not big enough for a larger-scale big-data analysis, and the data resources, which are limited to a local hospital, leading to the results not being generalized to other states. Those situations in which patients who sustained fatal falls and did not reach the trauma center make severely injured patients unaccounted for in this study. Whether a fall was interrupted by objects, such as building materials before hitting the ground, is unknown in this cohort of patients. Our data were limited to patients' hospital stay; no investigation has been performed after patients were discharged from the hospital.

Further research will be performed through the research of multiple medical centers. Long-term outcome follow-up studies will be performed with consideration of the outcomes from rehabilitation. At what height a fall becomes fatal under intentional vs. unintentional FFHs needs further investigation.

Conclusions

Intentional vs. unintentional FFHs yielded different injury patterns and injury severity as the injured patients from border falls had a lower ISS, and fewer head or chest injuries than domestic falls, although there were more extremity injuries in this study. MPNN analysis demonstrated that chest and head injuries with a low GCS indicated a high risk of mortality from a fall.

Acknowledgments: This research was performed at South Texas Health System – McAllen Department of Trauma, McAllen, TX, USA.

Research ethics: An ethics committee approval was obtained to conduct this retrospective study from the Western Institutional Review Board (South Texas Health System, 20216226).

Informed consent: Informed consent was obtained from all individuals included in this study, or their legal guardians or wards.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Use of Large Language Models, AI and Machine Learning Tools: MPNN, which was considered as a machine learning algorithm, was used in this study to stratify the importance of factors leading to server injury. The use of MPNN has been properly documented in the article.

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Data availability: Not applicable.

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