JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, January 2019, Vol. 64, No. 1
doi: 10.1111/1556-4029.13803
Available online at: onlinelibrary.wiley.com

PAPER

ANTHROPOLOGY

Samantha K. Rowbotham,[1] *M.Ar.Sc. (Hons); Soren Blau,*[2,1] *Ph.D.; Jacqueline Hislop-Jambrich,*[3] *Ph.D.; and Victoria Francis,*[2] *M.B.B.S., M.Sc.*

An Assessment of the Skeletal Fracture Patterns Resulting from Fatal High (>3 m) Free Falls*

ABSTRACT: The injury patterns resulting from fatal high (>3 m) free falls have previously been documented in clinical and medico-legal contexts; however, details relating specifically to the skeletal blunt force trauma (BFT) have been limited. This study aimed to augment what is known of the skeletal fracture patterns resulting from fatal high free falls. Skeletal trauma was analyzed from full-body postmortem computed tomography scans of 95 individuals who died following a high free fall. Fracture patterns were documented using the five general anatomical regions, axial and appendicular regions, and postcranial unilateral and bilateral regions. Patterns were analyzed in the context of the extrinsic and intrinsic variables that may influence fractures using multiple logistic regression. Fracture patterns involved all aspects of the skeleton, with 98.9% exhibiting polytrauma, and were influenced primarily by the height fallen, manner of death, and landing surface. This improved understanding of fracture patterns will augment anthropological interpretations of the mechanism of BFT in cases of suspected high falls.

KEYWORDS: forensic science, forensic anthropology, high free fall, skeletal trauma, blunt force trauma, fracture pattern, postmortem computed tomography

Free falls from a height (>3 m) constitute a high-energy vertical deceleration event that may result in fatality. Circumstances in which these fall events occur are usually intentional (i.e., jump), but can sometimes be accidental (i.e., slip/trip) and, more rarely, homicidal (i.e., push/kick), and they typically involve a bridge or elevated structure (e.g., high-rise balcony/roof). This particular mechanism of trauma occurs less frequently than most other fatal fall types (e.g., falls involving stairs, low free falls, and falls from standing heights), because high free falls rarely occur during regular daily living activities.

As the circumstances of each high free fall event are unique, the distribution of the resulting skeletal blunt force trauma (BFT) is often complex. This degree of complexity means that when cases of skeletonized human remains with BFT are recovered, and the circumstances surrounding the mechanism of that trauma are unclear but suggestive of a high fall, it is challenging for forensic anthropologists to establish the mechanism as a high fall from the fracture pattern alone. Anecdotal forensic anthropology case studies have highlighted this difficulty. Anthropologists have been required to differentiate the skeletal BFT resulting from a high fall with other types of trauma from an assault (1); differentiate the skeletal BFT resulting from vertical deceleration (i.e., impact from a fall) with horizontal deceleration (i.e., impact from a motor vehicle) (2), and have been required to re-create the circumstances of an individual's fall from their pattern of BFT alone (3). For anthropologists to accurately identify the BFT that results from the high fall in these types of complex BFT cases, it is first imperative to understand the possible fracture patterns that may result from a fatal high fall.

Trauma research investigating fracture patterns resulting from fatal high free falls have, in comparison to other types of fatal falls, been well documented (4). This research however, has primarily focused on documenting injury patterns for clinical medicine and forensic pathology applications which, as detailed in Rowbotham and Blau (4), are typically insufficient for forensic anthropology purposes. Within the context of informing injury prevention, clinical medicine research has examined injury patterns resulting from high falls based on the variables that influence a fall (5); the role/contribution of injuries and the fall's associated variables to mortality (6); clinical experiences with the management of these types of trauma cases (7–10); differentiating jumps (i.e., suicide) from falls (i.e., accident) (11); and simply presenting the types of possible injury patterns that may result from this BFT mechanism (12,13). Forensic pathology research has investigated high fall patterns of injury in two contexts. First, to document the epidemiology of fatal falls in specific populations, which includes providing details of injury patterns for cases that are either specifically suicides (14–17) or cases that cover all manners of death (18–21). Second, to specifically investigate the injury patterns that result from high falls in relation to mortality and/or the circumstances and manner of the death (22–24).

[1]Department of Forensic Medicine, Monash University, 65 Kavanagh Street, Southbank, Victoria 3006, Australia.
[2]Victorian Institute of Forensic Medicine, 65 Kavanagh Street, Southbank, Victoria 3006, Australia.
[3]Centre for Medical Research, Toshiba Medical, 12 – 24 Talavera Road, North Ryde, New South Wales 2113, Australia.
Corresponding author: Samantha K Rowbotham, M.Ar.Sc. E-mail: Samantha.Rowbotham@monash.edu

*Funding provided by the Australian Government Research Training Program Scholarship.

Received 23 Dec. 2017; and in revised form 21 Feb. 2018; accepted 29 Mar. 2018.

As skeletal injuries are a major component of high fall trauma, clinical practitioners and forensic pathologists have considered hard tissue trauma in their injury analyses; however, the level of this detail has been varied. Typically, skeletal trauma detail is referenced to the general anatomical regions of the body traumatized (e.g., fractures of the lower extremities) and details of skeletal injuries are not always differentiated from soft tissue injuries. Furthermore, in the clinical contexts, the skeletal injuries of individuals who have died are not always distinguishable from injuries of those who survived the trauma. Consequently, although research in these disciplines does inform anthropological examinations, the sparse detail pertaining to fracture patterns ensures their value in augmenting forensic anthropological analyses is restricted.

Injury pattern research specifically pertaining to skeletal fractures has been documented in some clinical and anthropological work. Clinically, Gulati et al. (25) and Teh et al. (26) have detailed the specific skeletal elements traumatized as a result of high falls. The nature of these trauma cases primarily comprising survivors however, means that the translation of these fracture patterns to cases of medico-legal significance (i.e., fatal) is limited, as fracture patterns are markedly different in survivable falls compared to fatal falls. Research that is specifically applicable to forensic anthropology practice has investigated fracture patterns resulting from bridge jumpers (27); the relationship of fracture patterns to the factors that influence a fall such as height and the manner of death (28,29); and anecdotal cases that highlight the variety of possible fracture patterns resulting from this fall type (30). This clinical and anthropological research provides some valuable detailed analyses of the skeletal elements susceptible to fracturing from this fall mechanism, as well as some details of the relationship of the fall circumstances relative to the distribution of those fractures. Both of which assist in augmenting the anthropologist's analysis and interpretation of skeletal BFT in cases of suspected high free falls.

The aim of this study was to further validate and strengthen these anthropological, clinical, and pathological findings for medico-legal purposes, by further investigating in detail, and in the context of the variables known to influence trauma, the skeletal fracture patterns that result from fatal high (>3 m) free falls.

Materials and Methods

A retrospective review of individuals who died following a fall from height in Victoria, Australia, between 2005 and 2014 was undertaken using the National Coronial Information System (NCIS) online database (31). Cases which documented the individual's intrinsic variables (i.e., age, sex, body mass index (BMI), psychoactive drug use, and pre-existing mental/physical conditions) and extrinsic variables (i.e., height fallen, manner of death, and landing surface) were included in the study. All cases were situations where the fall event was witnessed and so the fall was known to be the cause of trauma. None of these falls, as far as was possible to ascertain from the NCIS documentation, were falls where an object was impacted during the descent. A total of 95 cases met this study inclusion criteria.

The forensic pathology examination for each of these cases was conducted at the Victorian Institute of Forensic Medicine (VIFM) where, upon admission to the institute, the deceased underwent a routine full-body postmortem computed tomography (PMCT) scan (32). The associated VIFM PMCT scan for each of these 95 cases was then analyzed for skeletal trauma using axial and three-dimensional reconstructed formats. For cases admitted to the VIFM between 2005 and 2009, PMCT used the Aquilion 16™ Toshiba Medical System (tube voltage 120 kVp, 1.025 mm typical spatial resolution). For cases admitted since 2009, PMCT used the SOMATOM® Definition Flash, Siemens Healthcare (tube voltage 140 kVp). The Digital Imaging and Communications in Medicine (DICOM) axial dataset for each case was examined using the Siemens Healthcare Syngo.via® VB10B multimodality image viewing package. Each DICOM dataset comprised one small field-of-view (FOV) scan reconstructed at 1 mm contiguous slice thickness to view the head and neck (i.e., skull and cervical vertebrae) and one large FOV scan reconstructed at 2 mm contiguous slice thickness to view the body (i.e., remaining postcranial skeleton). In certain cases, the large FOV did not encompass the full postcranial skeleton. This was due to either the position of the remains within the bore of CT gantry when scanned, and/or if the individual was particularly obese or tall and thus did not fit within the FOV parameters. Thus, it must be considered that some skeletal fractures, particularly those of the feet and elbows, may not have been scanned and so could not be accounted for.

Skeletal trauma was recorded as present or absent for each of the 206 skeletal elements. For the purpose of descriptive statistics, the skeleton was grouped into 42 regions (Table 1). For the purpose of statistical analyses, fracture patterning was interrogated by the five general anatomical regions (i.e., skull/cervical vertebrae, thoracic cavity, upper extremities, pelvic girdle/lumbar vertebrae, and lower extremities), by the axial and appendicular regions, and by the unilateral and bilateral postcranial regions (i.e., ribs, upper extremities, os coxae, and lower extremities). Using the Statistical Package for the Social Sciences (SPSS) version 24, Fisher's exact tests were first employed to identify which of the recorded NCIS variables were associated with skeletal trauma at a significance of $p = \leq 0.25$ (33). The variables that showed significant relationships were then included in multiple logistic regression (backward Wald stepwise) models. For each model, odds ratios (OR) were used to describe the predicted likelihood of skeletal fracturing occurring in the context of the significant variable/s. Statistical significance was accepted at $p = \leq 0.05$. Predictive probabilities for each model were then tested for accuracy using the receiver operating characteristic and Hosmer–Lemeshow test.

Ethics approval for the research was granted by the Victorian Institute of Forensic Medicine Research Advisory and Ethics Committee (EC 7/2015).

Results

The circumstances of the 95 fatal high (>3 m) free falls in this study were primarily jumps from bridges/overpasses ($n = 27$) and buildings ($n = 44$), and accidental falls from buildings ($n = 9$). There was one case of homicide where, during an assault, an individual was pushed out of a window. Details of the study population's intrinsic and extrinsic variables are documented in Tables 2 and 3.

All 95 individuals exhibited BFT and this trauma involved all 42 regions of the skeleton. Of the 95 cases, one individual (1.1%) exhibited trauma to only a single skeletal region, an accidental fall off a 4 m high ladder, while the remaining 94 individuals (98.9%) exhibited polytrauma (Fig. 1). Distribution of fractures by height (Fig. 2) and by manner of death (Fig. 3) showed that all aspects of the skeleton were susceptible to fractures and that the frequency of these fractures were consistent

TABLE 1—*The 42 skeletal regions.*

Skeletal Region		Bones within that Region
Skull		
1	Cranial vault	Frontal + Parietals
2	Cranial base	Occipital + Temporals + Sphenoid
3	Facial bones	Maxillae + Zygomatics + Nasals + Ethmoid + Vomer + Palatines + Inferior Nasal Conchae + Lacrimals + Mandible
Vertebrae		
4	Cervical	C1–C7 + Hyoid
5	Thoracic	T1–T12
6	Lumbar	L1–L5
Thoracic cavity		
7	Ribs (left)	R1–R12
8	Ribs (right)	R1–R12
9	Sternum	
Right upper extremity		
10	Clavicle	
11	Scapula	
12	Humerus	
13	Radius	
14	Ulna	
15	Carpals	Trapezium + Trapezoid + Capitate + Hamate + Scaphoid + Lunate + Triquetrum + Pisiform
16	Metacarpals	MC1–MC5
17	Phalanges	Proximal 1–5 + Intermediate 1–4 + Distal 1–5
Left upper extremity		
18	Clavicle	
19	Scapula	
20	Humerus	
21	Radius	
22	Ulna	
23	Carpals	Trapezium + Trapezoid + Capitate + Hamate + Scaphoid + Lunate + Triquetrum + Pisiform
24	Metacarpals	MC1–MC5
25	Phalanges	Proximal 1–5 + Intermediate 1–4 + Distal 1–5
Pelvic girdle		
26	Os Coxa (left)	
27	Os Coxa (right)	
28	Sacrum	
Right lower extremity		
29	Femur	
30	Patella	
31	Tibia	
32	Fibula	
33	Tarsals	Talus + Calcaneus + Navicular + Cuboid + Cuneiforms (lateral, intermediate, medial)
34	Metatarsals	MT1–MT5
35	Phalanges	Proximal 1–5 + Intermediate 1–4 + Distal 1–5
Left lower extremity		
36	Femur	
37	Patella	
38	Tibia	
39	Fibula	
40	Tarsals	Talus + Calcaneus + Navicular + Cuboid + Cuneiforms (lateral, intermediate, medial)
41	Metatarsals	MT1–MT5
42	Phalanges	Proximal 1–5 + Intermediate 1–4 + Distal 1–5

C, cervical; T, thoracic; L, lumbar; R, rib; MC, metacarpal; MT, metatarsal.

TABLE 2—*Descriptive statistics of the study population variables.*

Variables	Frequency	%
Intrinsic Variables		
Sex		
Male	73	76.8
Female	22	23.2
Age*		
≤34 years	47	49.5
≥35 years	48	50.5
BMI		
Under/normal weight	36	37.9
Over/obese weight	59	62.1
Psychoactive drugs		
Present	84	88.4
Absent	11	11.6
Pre-existing conditions (mental/physical)		
Present	84	88.4
Absent	11	11.6
Extrinsic variables		
Height of fall		
3–25 m	49	51.6
26–50 m	24	25.3
≥51 m	22	23.2
Manner of death		
Accident	19	20
Suicide	75	78.9
Homicide	1	1.1
Landing Surface		
Deformable (i.e., soft)	13	13.7
Nondeformable (i.e., hard)	82	86.3

*Division of the age ranges at 35 years was taken from the population median.

TABLE 3—*The frequency of individuals relative to the extrinsic variables.*

	Height of Fall					
	3–25 m		26–50 m		≥51 m	
	D	N-D	D	N-D	D	N-D
Accident	0	14	0	3	2	0
Suicide	1	33	1	20	9	11
Homicide	0	1	0	0	0	0

D, deformable surface; N-D, nondeformable surface.

regardless of the fall height involved and if the fall was an accident or suicide. Overall, fractures of the axial skeleton occurred slightly more frequently than the appendicular skeleton; a ratio that was fairly consistent across the three height ranges (i.e., 3–25 m, 26–50 m, and ≥51 m) and the two primary manners of death (i.e., accident and suicide). The single homicide case exhibited fractures of the skull base and thoracic vertebrae only. Distribution of fractures by the surface landed on exhibited a contrasting pattern (Fig. 4). While all skeletal elements were susceptible to fracturing with both deformable and nondeformable landing surfaces, there was a substantial increase in the frequency of fractures, particularly in the axial region, in falls onto nondeformable surfaces compared with falls onto deformable surfaces.

When assessed by the five general anatomical regions, the distribution of fractures across the postcranial skeleton was associated with a number of variables (Table 4). Individuals were more likely to fracture their thoracic cavity if they intentionally jumped (OR 13.9) and their upper extremities if they were under the influence of psychoactive drugs (OR 16). Fractures of the pelvic girdle/lumbar vertebrae were more likely to occur if an individual was under the influence of psychoactive drugs (OR 6.8) and landed on nondeformable surfaces (OR 9.2). Individuals were also more likely to fracture their lower extremities if they intentionally jumped (OR 12.1) and/or landed on nondeformable surfaces (OR 7.1).

Fractures of only the axial skeleton occurred in 12 individuals (12.6%), with the remaining 83 individuals (87.4%) fracturing both their axial and appendicular skeleton. No individual fractured only their appendicular skeleton. Individuals who intentionally jumped and/or landed on nondeformable surfaces were less likely to fracture only their axial skeleton (OR 0.04 and OR 0.02, respectively) and thus were more likely to fracture both

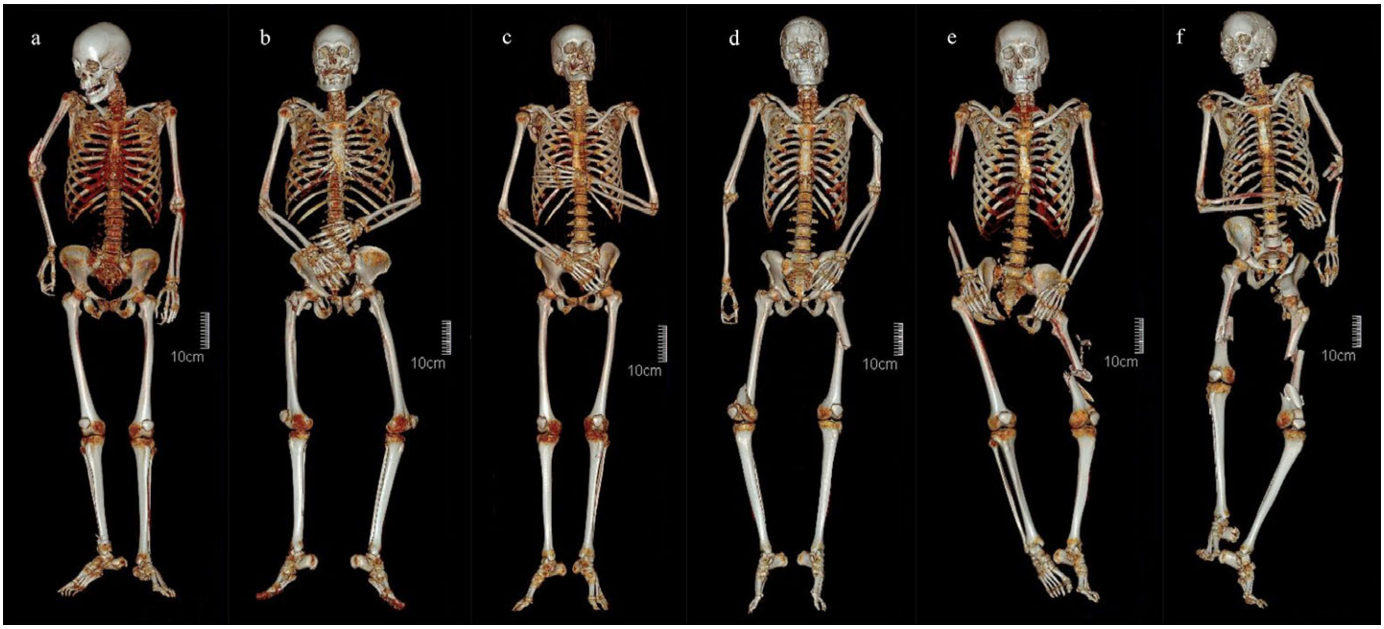

FIG. 1—*Examples of skeletal polytrauma resulting from fatal high falls. The PMCT scans show volume rendered anterior views of the full skeleton from falls of 9 m (a), 12 m (b), 12 m (c), 24 m (d), 63 m (e), and 84 m (f) onto nondeformable surfaces. NB: in cases d, e, and f, aspects of the elbows and lateral forearms were outside the CT FOV and subsequently could not be investigated for possible skeletal fractures. [Color figure can be viewed at wileyonlinelibrary.com]*

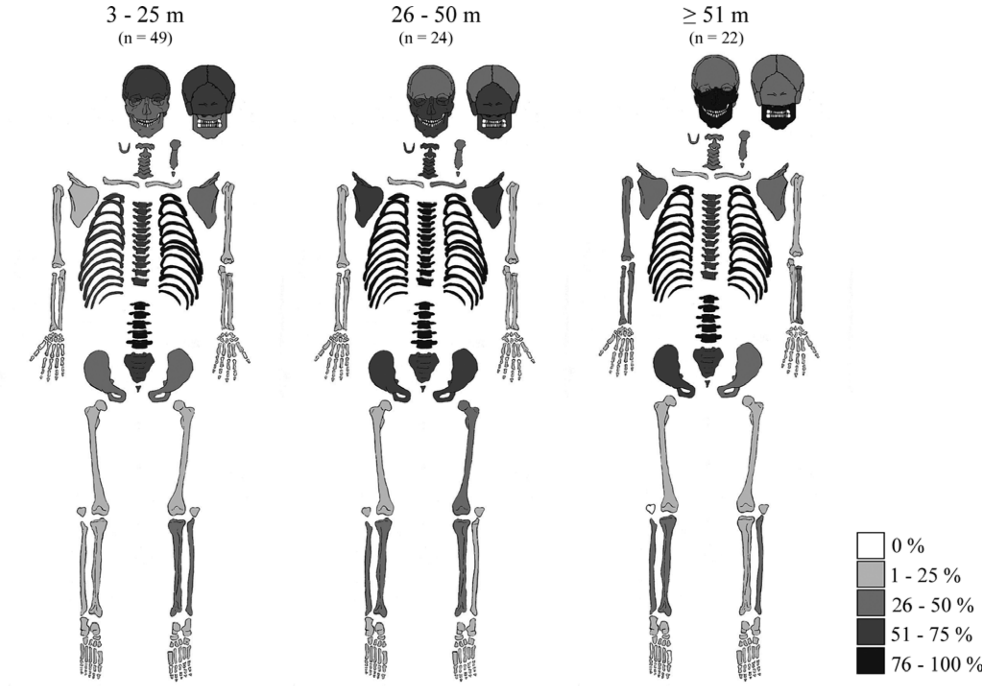

FIG. 2—*The frequency and distribution of fractures as related to the height fallen.*

their axial and appendicular skeleton (OR 28.1 and OR 48, respectively), than individuals who accidentally fell and/or landed on deformable surfaces (Table 5).

Postcranial bilateral fractures consistently occurred in these high free falls. Bilateral fractures across the postcranial skeletal elements (i.e., a combination of ribs, upper extremities, os coxae, and/or lower extremities) were more likely to occur if the landing surface was nondeformable (OR 14.2) and if the individual jumped rather than fell (OR 10.1) (Table 6). Comparatively, postcranial unilateral fractures were less likely to occur if the landing surface was nondeformable (OR 0.1) (see Table 6). These fracture patterns are further exemplified by the bilateral and unilateral fracture patterns resulting from the individual postcranial regions (i.e., ribs, upper extremities, os coxae, and lower extremities) (see Table 6). Those who jumped and/or those who landed on a nondeformable surface were more likely to

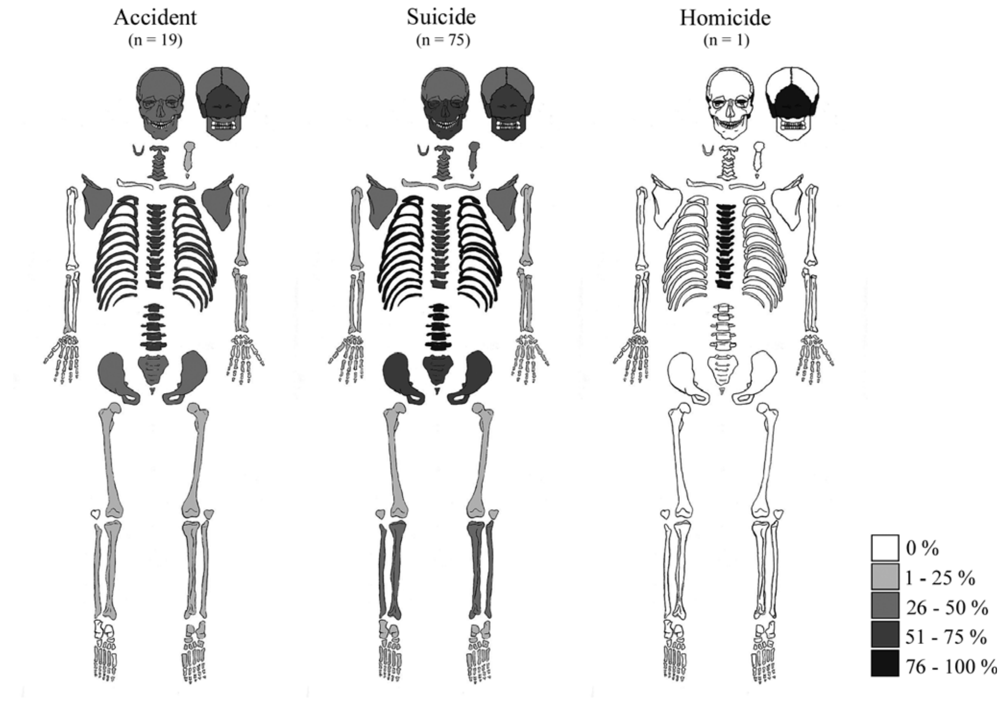

FIG. 3—*The frequency and distribution of fractures as related to the manner of the death.*

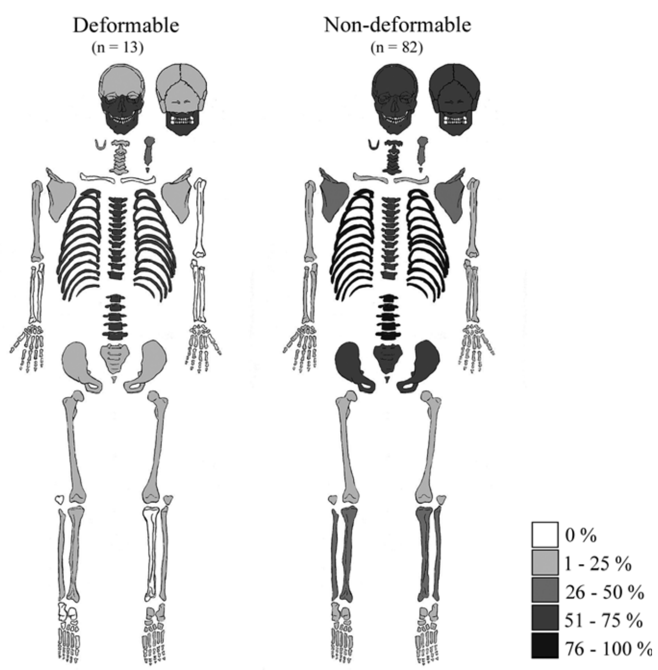

FIG. 4—*The frequency and distribution of fractures as related to the surface landed on.*

fracture their ribs bilaterally (OR 6.2 and OR 5.3, respectively). Rib fractures were also more likely to be bilateral (OR 3.1), and subsequently less likely to be unilateral (OR 0.1), if the individual was overweight/obese, compared with those who were of an under/normal weight. Fractures of the upper extremity were more likely to occur bilaterally if the individual intentionally jumped (OR 5.4), and were less likely to occur unilaterally as the height of the fall increased from 3–25 m to ≥51 m (OR 0.2). Bilateral fractures of the os coxae were more likely to occur as the height of the fall increased (OR 2.8 and OR 6.2 respective to height), and thus unilateral fractures were less likely to occur as the fall height increased (OR 0.2 and OR 0.2 respective to height). Bilateral os coxae fractures were also more likely to occur if the landing surface was nondeformable (OR 13.6). Unilateral os coxa fractures were less likely to occur in individuals who were older (≥35 years) (OR 0.3) and/or individuals who were overweight/obese (OR 0.3). Bilateral fractures of the lower extremities were more likely to occur if the individual intentionally jumped (OR 13.5) and/or landed on a nondeformable surface (OR 8.4).

Discussion

Extrinsic and Intrinsic Variables

The variables that primarily influenced how fractures distribute across the body in these high (>3 m) free falls were the physical properties of the fall (i.e., height fallen and landing surface) and the manner of the death; that is, the extrinsic variables. These same variables have been found by Warner and Demling (34), Snyder (35), and Tan and Porter (36) to have the most effect on high fall fracture patterns.

The variable of height plays a significant role in fracturing, not surprisingly, as the height of an individual's fall is directly proportional to the velocity of their body on impact (37). That is, the vertical deceleration energy on impact increases as the height fallen increases, and so the higher the fall, the greater the distribution and severity of the fractures on impact (e.g., 16,38).

The landing surface also influences the distribution and severity of skeletal trauma because, as Warner and Demling (34) and Tan and Porter (36) note, the principles of physics dictate that the type of surface material determines the duration of the impact on landing. In cases where the landing surface is nondeformable (e.g., concrete and bitumen), the duration of the impact is very short; that is, there is an abrupt deceleration force to the body on impact. Because these types of surface materials can

TABLE 4—*Skeletal fractures recorded in the five general anatomical regions.*

		Multiple Logistic Regression (Backward Wald Stepwise), Final Model					
						Predictive Probability	
	Frequency (%)	OR	95% CI	B	*p* value	ROC	H-L (Significance)
Skull + Cervical	79 (83.2)					0.615	0
BMI (over/obese weight)		0.322	0.085–1.219	−1.134	0.095		
Thoracic cavity	91 (95.8)					0.788	0
Manner of death					0.086		
Manner of death (suicide)		13.875	1.354–142.149	2.63	0.027*		
Manner of death (homicide)		NA					
Upper extremities	74 (77.9)					0.896	0.675 (0.879)
Psychoactive drugs (yes)		16.032	1.876–136.992	2.775	0.011*		
Manner of death					0.222		
Manner of death (suicide)		3.705	0.843–16.285	1.31	0.083		
Manner of death (homicide)		NA					
Landing surface (nondeformable)		NA					
Pelvic girdle + Lumbar	78 (82.1)					0.732	0.024 (0.877)
Psychoactive drugs (yes)		6.848	1.734–27.044	1.924	0.006*		
Landing surface (nondeformable)		9.162	1.853–45.294	2.215	0.007*		
Lower extremities	65 (68.4)					0.804	1.487 (0.829)
Manner of death†					<0.001*		
Manner of death (suicide)		12.120	3.497–42.01	2.495	<0.001*		
Manner of death (homicide)		NA					
Landing surface (nondeformable)		7.064	1.786–27.942	1.955	0.005*		
BMI (over/obese weight)		2.819	0.968–8.214	1.036	0.057		

*Statistically significant.
†Nature of this relationship is unknown and as such has not been discussed.
NA, sample size is too small to draw valid conclusions from and as such has not been discussed; OR, odds ratio; CI, confidence interval; B, beta; ROC, receiver operating characteristic; H-L, Hosmer–Lemeshow.

TABLE 5—*Skeletal fractures recorded in the axial and appendicular regions.*

		Multiple Logistic Regression (Backward Wald Stepwise), Final Model					
						Predictive Probability	
	Frequency (%)	OR	95% CI	B	*p* value	ROC	H-L (Significance)
Axial	12 (12.6)					0.935	1.764 (0.623)
Manner of death†					0.016*		
Manner of death (suicide)		0.036	0.004–0.343	−3.336	0.004*		
Manner of death (homicide)		NA					
Landing surface (nondeformable)		0.021	0.002–0.210	−3.873	0.001*		
BMI (over/obese weight)		0.219	0.043–1.112	−1.521	0.067		
Appendicular‡	0 (0)						
Axial + Appendicular	83 (87.4)					0.935	1.764 (0.623)
Manner of death†					0.016*		
Manner of death (suicide)		28.104	2.915–270-985	3.336	0.004*		
Manner of death (homicide)		NA					
Landing surface (nondeformable)		48.081	4.769–484.796	3.873	0.001*		
BMI (over/obese weight)		4.576	0.899–23.278	1.521	0.067		

*Statistically significant.
†Nature of this relationship is unknown and as such has not been discussed.
‡Not relevant.
NA, sample size is too small to draw valid conclusions from and as such has not been discussed; OR, odds ratio; CI, confidence interval; B, beta; ROC, receiver operating characteristic; H-L, Hosmer–Lemeshow.

not attenuate the deceleration forces, almost all of the energy generated from the fall is transmitted to the body (34). Deformable surfaces by comparison, which were all water in this study, allow for a longer impact duration because the body is able to move through the surface material (35). In these cases, there is some time for the landing surface material to attenuate some of the deceleration force on impact, and thus, less energy is transmitted directly to the body. Consequently, fewer fractures are likely to result from landings on deformable surfaces than landings on nondeformable surfaces. Furthermore, because a body moves through water, individuals who land on a deformable surface sustain only one landing position and thus are not subjected to additional impacts, or ‘bounces’, that landing on nondeformable surfaces entail; this would again minimize the distribution and severity of fractures. It should also be noted that, although fractures resulting from landings on deformable surfaces may not be as severe as those resulting from landings on nondeformable surfaces, and in some cases they are arguably

TABLE 6—*Skeletal fractures recorded in the postcranial unilateral and bilateral regions.*

		Multiple Logistic Regression (Backward Wald Stepwise), Final Model					
						Predictive Probability	
	Frequency (%)	OR	95% CI	B	*p* value	ROC	H-L (Significance)
Unilateral	10 (10.5)					0.775	0.153 (0.696)
Landing surface (nondeformable)		0.099	0.022–0.443	−2.314	0.002*		
Preconditions (yes)		0.221	0.040–1.229	−1.51	0.085		
Bilateral	80 (84.2)					0.810	0.048 (0.826)
Landing surface (nondeformable)		14.243	2.914–69.603	2.656	0.001*		
Manner of death†					0.010*		
Manner of death (suicide)		10.085	2.278–44.656	2.311	0.002*		
Manner of death (homicide)		NA					
Unilateral ribs	16 (16.8)					0.723	0
BMI (over/obese weight)		0.145	0.043–0.497	−1.928	0.002*		
Bilateral ribs	69 (72.6)					0.778	0.952 (0.917)
Landing surface (nondeformable)		5.313	1.393–20.261	1.67	0.014*		
BMI (over/obese weight)		3.127	1.097–8.912	1.14	0.033*		
Manner of death†					0.011*		
Manner of death (suicide)		6.159	1.889–20.079	1.818	0.003*		
Manner of death (homicide)		NA					
Unilateral upper extremity	30 (31.6)					0.65	0 (1)
Height fallen†					0.046*		
Height fallen (26–50 m)		0.444	0.150–1.313	−0.811	0.142		
Height fallen (≥51 m)		0.211	0.055–0.806	−1.558	0.023*		
Bilateral upper extremity	44 (46.3)					0.732	0 (1)
Landing surface (nondeformable)		NA					
Manner of death†					0.027*		
Manner of death (suicide)		5.417	1.584–18.525	1.689	0.007*		
Manner of death (homicide)		NA					
Unilateral Os Coxa	21 (22.1)					0.753	2.793 (0.903)
Height fallen†					0.028*		
Height fallen (26–50 m)		0.169	0.036–0.782	−1.78	0.023*		
Height fallen (≥51 m)		0.202	0.044–0.928	−1.598	0.040*		
Age (≥35 years)		0.286	0.088–0.931	−1.253	0.038*		
BMI (over/obese weight)		0.328	0.113–0.952	−1.116	0.040*		
Bilateral Os Coxae	38 (40.0)					0.696	0.008 (0.996)
Height fallen†					0.018*		
Height fallen (26–50 m)		2.826	1.018–7.840	1.039	0.046*		
Height fallen (≥51 m)		6.216	1.466–26.350	1.827	0.013*		
Landing surface (nondeformable)		13.646	1.938–96.09	2.613	0.009*		
Unilateral lower extremity‡	34 (35.8)						
Bilateral lower extremity	31 (32.6)					0.697	0.015 (0.993)
Landing surface (nondeformable)		8.427	1.022–69.469	2.132	0.048*		
Manner of death†					0.049*		
Manner of death (suicide)		13.477	1.690–107.460	2.601	0.014*		
Manner of death (homicide)		NA					

*Statistically significant.
†Nature of this relationship is unknown and as such has not been discussed.
‡No final model.
NA, sample size is too small to draw valid conclusions from and as such has not been discussed; OR, odds ratio; CI, confidence interval; B, beta; ROC, receiver operating characteristic; H-L, Hosmer–Lemeshow.

insufficient to alone have caused fatality, such fractures may lead to other complications like drowning (e.g., 27,39), which in turn results in the fatality.

The manner of death (i.e., suicide or accident) may influence both the landing position and the height fallen, and thus this variable also effects the distribution of fractures. Different landing positions have been hypothesized for different manners of death. Teh et al. (26) have suggested that individuals who intentionally jump tend to land feet-first, and Christensen (40) has suggested that those who are unconscious (i.e., possible accident or homicide cases) tend to align in the natural gravitational position of horizontal during a fall. These different landing positions result in markedly different distributions of fractures (35,41). With regard to the height fallen, individuals who jump tend to do so from greater heights than individuals who accidentally fall (e.g., 29,42). This is likely because individuals who intentionally jump are deliberately seeking the greatest height available to them (e.g., 43), while accidental falls occur on a daily basis and so typically involve lower heights associated with daily activities (e.g., multilevel car park or the roof of a double-story house). As the height informs the deceleration velocity transmitted to the body on impact, the greater heights usually involved with intentional jumps mean suicides are more likely to result in a greater distribution and severity of fractures than accidental falls.

Furthermore, the extrinsic variable of landing position, although it could not be accounted for in this study (see Limitations), may also influence the distribution of fractures. The nature of these high-energy vertical deceleration events mean that, upon impacting the landing surface, the body is susceptible to both direct and indirect forces. Both types of forces may result from any landing position; although the occurrence of both forces is usually more apparent in vertical landing positions (i.e., head-, feet-, or buttock-first impacts), where there is substantial body surface for the energy to dissipate through after the initial impact. An individual's susceptibility to both direct and indirect forces with these falls, from both primary and secondary/bounce impacts with vertical and horizontal landing positions, means a widespread distribution of fractures is common; an observation highlighted anecdotally by Rowbotham (30).

Intrinsic variables have been found by Lapostolle et al. (44), İçer et al. (45), and Obeid et al. (22) to also influence fractures from a high fall. Findings from this study however, demonstrate that intrinsic variables have little influence on fracture patterns when the extrinsic variables of the fall are also considered. The presence of pre-existing mental/physical conditions, while possibly influencing how and why the fall event occurred, showed no association with fracture patterns. Similarly, the variables of age and sex played only a minor role in influencing fracture patterns; a result not unexpected given that the population demographic primarily comprised healthy young and middle-aged adults. The variables of psychoactive drugs and BMI did influence the distribution of fractures. In this study, psychoactive drugs were present in most of the suicide cases (71%), many of the accident cases (42%), and were involved in the one homicide case (100%). Although it is difficult and subjective to infer an individual's mental and physical behavioral response while under the influence of psychoactive drugs, it is possible that the reaction mechanisms of the individuals in this study were altered from the effects of the drugs and that these behaviors may have influenced how they landed. The variable of BMI was largely associated with fractures indirectly as a person's body mass effects their deceleration velocity at impact (34), which in turn influences the severity and distribution of their fractures.

Skeletal Fracture Patterns

The pattern of skeletal BFT in this study, that is trauma distributed across the full skeleton with a slightly greater frequency in the thoracic and skull regions, is similar to that found in other fatal high falls (15,16,28,43,46,47). The presence of polytrauma, regardless of the height fallen, surface landed on, or the manner of the death, suggests that all aspects of the skeleton were susceptible to fractures from this fall type. Polytrauma was substantially more present in this study (98.9% of cases) than in other high fall studies (29,47). This finding is likely attributed to the fact that most other studies did not include many cases of falls over 25 m in height. It is therefore interesting to note that this study did not show a positive correlation between an increase in the frequency of fractures and an increase in the height fallen (see Fig. 2), as has been previously identified (18,20,29,38,48). This study did, however, identify a number of significant fracture patterns.

Five General Anatomical Skeletal Regions—Fractures of the skull/cervical vertebrae occurred in almost all fatal falls (83.2%). This statistic is similar to other fatal high falls (20,28,38,43,49) and other fatal fall types (4) and is an expected finding given head injuries have commonly been associated with mortality in falls. Although different aspects of the skull fractured depending on the height fallen, the manner of death, and the landing surface, none of these patterns were identified as significant. This indicates there was no unique distribution of skull/cervical vertebrae fractures relative to the various circumstances of a free fall when that fall is from a height; a finding in contrast to low (≤3 m) free falls (50).

The thoracic cavity was the most frequently fractured region of the skeleton (96%). This region, particularly the ribs, has generally been considered the skeletal area that is most commonly traumatized in high falls (24,29), and this may be attributed to the rib cage's susceptibility to fractures from almost any landing position. Fractures of this region were more likely to occur in those who jumped than in those who accidentally fell. Similarly, fractures of the rib cage have commonly been found with intentional jumps from heights (14,16,17,24,38), with serial rib fractures even being termed the 'hallmark' sign of suicide bridge jumpers (27), and have been less frequently found in accidental cases (11,26). Explanations for this association with suicide may be attributed to the fall height involved. Intentional jumps occurred across all three height ranges, while accidental falls occurred almost exclusively (74%) from only the lowest height range (3–25 m). As a positive correlation has previously been identified between an increase in rib fractures and an increase in the height fallen (18,20,49,51), fractures of the thoracic cavity are more likely to occur with the greater height fallen, which in this study was almost exclusively cases of suicides.

Upper extremity fractures also commonly resulted from high falls (77%) and were more likely to occur if an individual was under the influence of psychoactive drugs. Given individuals likely had their physical reactions during the fall altered as a result of the effects of psychoactive drugs, one possible explanation for the significance of this variable is as follows. Those individuals overly active would be alert and thus would likely be flailing their arms, during the descent. With arms outstretched from the torso, the upper extremities would be susceptible to experiencing their own direct impact on either the primary and/or secondary landing positions. For individuals who were overly passive during the descent, it has been hypothesized by Christensen (40) that such individuals, that is those who are less responsive and nonresisting during a fall, tend to land in the more gravitationally aligned position of horizontal. This landing position would ensure the upper extremities are exposed a direct impact on landing.

Fractures of the pelvic girdle/lumbar vertebrae require a large amount of force (52) and are often associated with high falls (18,28,29); a relationship evident in this study with 82% of cases exhibiting fractures of this region. These fractures were more likely to occur in individuals who landed on nondeformable surfaces and/or were under the influence of psychoactive drugs. The nature of the nondeformable landing surface ensures, as previously detailed, that a greater energy is transmitted to this skeletal region, either from a direct impact or indirect axial force, than would be transmitted from a deformable landing surface. Furthermore, the body is susceptible to secondary/bounce impacts when landing on nondeformable surfaces. Multiple landing positions ensure, similar to the thoracic, that the pelvic girdle/lumbar vertebrae are likely to be subjected to force from at least one of these impacts and thus are more likely to fracture. Presence of psychoactive drugs suggests that both vertical and horizontal landing positions may result from an individual's overactive or overpassive behavioral state. Individuals who were more agitated would have been conscious during the fall, so may have been capable of maneuvering their body into the natural feet-first position (e.g., 53), while those who were less able to react are, as previously discussed, more likely to fall in the natural gravitational position of horizontal (40). In both landing positions, the pelvic girdle/lumbar vertebrae would be susceptible to fractures with indirect axial forces from the vertical landings, and direct forces from the horizontal landings (35,41).

Lower extremity fractures typically result from feet-first landings and were the skeletal region most infrequently fractured (68.4%) in this study. The low frequency of these fractures may be attributed to feet-first landing positions more commonly resulting in survival (13); a finding possibly attributed to the body's vital organs not being traumatized from the direct primary impact. Feet-first landings, and thus fractures of the lower extremities, have been commonly found with intentional jumps (11,42,43). Explanations for the relationship between lower extremity fractures and suicides in this study may be because individuals who intentionally jump are generally conscious and aware of what they are doing (53), as opposed to accidental falls where individuals may be in shock or unconscious, and thus they may be capable of maneuvering into or maintaining an upright body position (e.g., 53). Fractures of the lower extremities were also more likely to result if the landing surface was nondeformable. As previously discussed, the inability of a nondeformable surface to attenuate some of the body's deceleration energy on impact ensures that individuals who land feet-first sustain a greater force to their lower extremities than those who land on a deformable surface would.

Axial and Appendicular Skeletal Regions—The distribution of fractures across the axial and appendicular skeleton showed that trauma always involved some aspect of the axial skeleton in these high falls. Considering these falls were fatal and that the axial skeleton houses the body's vital organs, this finding is unsurprising.

Fractures of both the axial and appendicular skeleton, as opposed to the axial skeleton alone, were more likely to result if an individual landed on a nondeformable surface. This pattern has been well supported in the literature. Fractures of the ribs, skull, and vertebrae (i.e., axial skeleton) have been primarily found with deformable surface landings (14,27), while fracture patterns that also involve the extremities have been more commonly associated with nondeformable surface landings (7,29). Possible explanations for this are twofold. First, as the physical properties of nondeformable landing surfaces do not attenuate the deceleration energy on impact, there is more energy for the body to attenuate and thus more regions of the skeleton likely to be involved in order for all that energy to dissipate, than required from a deformable surface. Second, as previously detailed, secondary/bounce impacts are only possible with nondeformable landing surfaces. As such, even if the initial fall did only involve the axial skeleton (e.g., head-first primary impact), there would be subsequent impacts to the body and these would likely involve the appendicular skeleton (e.g., the secondary impact would then be falling onto the upper extremities).

Fractures of both the axial and appendicular skeleton were also more likely to occur if the individual intentionally jumped, rather than accidentally fell; a finding further statistically supported with fractures of only the axial skeleton being less likely to occur if the individual intentionally jumped. As previously detailed, the heights fallen in individuals who intentionally jump are typically greater than the heights involved for accidental falls. Consequently, the greater heights for the intentional jumps generate a greater vertical deceleration force on impact, which likely result in a wider distribution and greater severity of fractures than in accidental falls. This observation has previously been found in both clinical (26) and mortuary (29) contexts. Furthermore, the feet-first landing position, which has been associated with intentional jumps (11,26), is a landing position that results in fractures of both the appendicular and axial skeleton. The lower extremities are susceptible to direct impact forces with the axial skeleton subjected to indirect axial forces, and/or direct forces from a secondary impact where the individual then falls anteriorly or posteriorly onto the torso.

Unilateral and Bilateral Skeletal Regions—Bilateral fractures of the postcranial skeleton were, as has also been found by Petaros et al. (29), more likely to result in individuals who intentionally jumped. This finding suggests, and further supports the previous hypothesis, that when an individual intentionally jumps, they tend to do so from greater heights than accidental falls and so they generate a greater vertical deceleration force on impact. In order for the body to attenuate this greater deceleration energy, it is likely both sides of the skeleton would be required to dissipate these forces. Bilateral fractures were also more likely to occur if the landing surface was nondeformable, a result further supported statistically by unilateral fractures being less likely to result from landing on nondeformable surfaces. This finding also reinforces previous discussion points that a body landing on a nondeformable surface will experience secondary/bounce impacts, and that with multiple impacts, both sides of the skeleton would likely be affected.

Bilateral rib fractures were more likely to occur in individuals who intentionally jumped. This fracture pattern indicates a direct impact to the thorax, either anteriorly or posteriorly, a finding further supported by the relatively high frequency of sternal (36%) and scapula (55%) fractures in this study. Although there was no statistical correlation between bilateral rib fractures and height, a finding dissimilar to Petaros et al. (29) and Atanasijevic et al. (51), their association with intentional jumps, which are usually from greater heights than accidental falls, suggests they may be indirectly associated with height. Bilateral rib fractures were also more likely to result from landings on nondeformable surfaces. This may be attributed to the thorax's susceptibility to anterior/posterior direct impact, and thus bilateral fractures, from both primary landing positions (i.e., horizontal) as well as secondary landing positions (i.e., falling anteriorly or posteriorly after a vertical landing) (41), when the surface is nondeformable.

Upper extremities were also more likely to fracture bilaterally if the individual intentionally jumped. This may be because individuals are often conscious and aware of their fall when intentionally jumping (e.g., 53) and so, when conscious, it is a natural instinct for a person to outstretch their arms on impact. Unilateral upper extremity fractures also become less likely to occur as the height of the fall increases. As previously discussed, the greater the height fallen the greater the deceleration energy is on impact for the body to attenuate, and thus, it is less likely only one side of the body would be sufficient to absorb all of that force and thus fracture.

Bilateral fractures of the os coxae were more likely to occur as the height of the fall increased, a finding further supported by unilateral os coxa fractures being less likely to occur as the fall height increased. This may be attributed both to the pelvic girdle being more likely to fracture as the height of a fall increases (29), and because bilateral fractures may result from both direct forces (i.e., horizontal impacts) and indirect forces (i.e., vertical impacts).

Unilateral fractures of both the ribs and the os coxa were less likely to occur in individuals with high BMIs, a finding that was further supported by the pattern of bilateral rib fractures being more likely to occur in individuals with high BMIs. Individuals with high BMIs will have generated a greater impact force as a result of their larger body mass (34,36). This greater impact force would likely involve more aspects of the body to absorb the force (i.e., both sides of the skeleton) than would be necessary for an underweight/normal weight individual. Unilateral fractures of the os coxa were also less likely to occur in the older (≥35 years) individuals. Given this study population mostly included young and middle-aged adults, biological differences with age are unlikely to influence fracture patterns. Rather, this may suggest that older individuals were less likely to be landing laterally than the younger individuals.

Bilateral fractures of the lower extremities were also more likely to result in individuals who intentionally jumped rather than accidentally fell, and in those who landed on nondeformable surfaces compared to those who landed on deformable surfaces. This finding further reinforces previous discussion points that suicide jumps tend to result in feet-first landings (11,26) and that this landing position often results in lower extremity fractures (41). As previously discussed, this relationship may be because these individuals were conscious during their falls and so were capable of controlling their body movement (e.g., 53), and/or because they may have already been aligned in the feet-first position as that was the position they initiated the fall in. Furthermore, feet-first landings onto nondeformable surfaces mean the feet, a relatively small surface area (35), are required to absorb all generated deceleration force on impact, unlike landings on deformable surfaces. As this high degree of force is only transmitted through the feet, it is likely both lower extremities would be required to absorb the force and thus they would both fracture.

Overall, the lack of unilateral fracture distributions in this study, as most patterns resulted in bilateral trauma, suggests individuals do not have a tendency to land on one particular side of the body. It has been previously hypothesized by Kremer et al. (54) and further suggested by Abel and Ramsey (27) and Teh et al. (26), that the lateralization of trauma may be related to a person's dominant side, which for most individuals is the right; a hypothesis the results of this study do not support.

Limitations

In addition to the methodological limitations identified with using the VIFM PMCT data outlined previously, there were a number of limitations in this study that influence the contextual interpretations of the identified skeletal fracture patterns. First, the nature of the retrospective data collection means only the details of the fall event reported in the NCIS were able to be accounted for in this study. Variables such as the position of the body on impact (35,44) and the influence of aerodynamic drag and wind shear during the fall (34,35,37), all of which have been noted to be extrinsic variables that will influence trauma in cases of high falls, were unable to be accounted for as they were rarely documented in the NCIS. Second, the small sample size (n = 95) and the categorical nature of most variables in this study, meant variables had to be grouped into relatively broad subcategories. For example, to cover the height range of 3–97 m in this study, heights were grouped only into three categories, even though the principles of physics dictate that within each height range (e.g., 3–25 m) there will be substantial variation in the amount of energy generated as a result of the fall height. Consequently, it is acknowledged these generalized categories mean some detail is lost in contextualizing and interpreting the resulting fracture patterns.

Conclusion

Skeletal BFT resulted from every case of a fatal high (>3 m) free fall. Trauma was almost exclusively polytrauma that involved, at a minimum, the individual's axial skeleton. The distribution of these fractures was primarily informed by the extrinsic variables of the fall (i.e., fall height, landing surface, and manner of death). A number of fracture patterns characteristic of this fatal fall type were identified. In the context of all extrinsic and intrinsic variables, key observations comprise:

- Thoracic fractures were more likely to result from intentional jumps than accidental falls;
- Pelvic and lower extremity fractures were more likely to result if the landing surface was nondeformable;
- Both axial and appendicular fractures together were more likely, and axial fractures alone were less likely, to result if the fall was intentional (i.e., jump) and the landing surface was nondeformable; and
- Postcranial fractures were more likely to result bilaterally if the fall was intentional, the landing surface was nondeformable, and the height fallen was over 25 m.

To fully augment these identified fracture patterns, further contextual investigation into the pathophysiology of skeletal trauma from high falls is required. The biophysical principles of impact force, impact energy, duration of impact, and force distribution, as outlined in Warner and Demling (34) and Tan and Porter (36), are beyond the scope of this study but are nonetheless recommended for future work.

In conclusion, this contextual and detailed analysis of skeletal fractures further validates and augments the BFT patterns reported in the clinical and forensic medical literature. Strengthening this current understanding of the possible skeletal fracture patterns resulting from fatal high falls will further assist anthropologists with their interpretations of BFT in cases where the mechanism of a high free fall is suspected to have contributed to an individual's death.

Acknowledgments

The authors wish to thank the National Coronial Information System for their assistance with attaining the coronial cases; the Victorian Institute of Forensic Medicine for access to each case's associated PMCT DICOM dataset; and the two anonymous reviewers for their constructive comments on the manuscript.

References

1. Finegan O. Case study 4.1: the interpretation of skeletal trauma resulting from injuries sustained prior to, and as a direct result of, freefall. In: Kimmerle EH, Baraybar JP, editors. Skeletal trauma: identification of injuries resulting from human rights abuse and armed conflict. Boca Raton, FL: Taylor and Francis Group, 2008;181–95.
2. Tomczak PD, Buikstra JE. Analysis of blunt trauma injuries: vertical deceleration versus horizontal deceleration injuries. J Forensic Sci 1999;44(2):253–62.
3. Introna F, De Donno A, Santoro V, Corrado S, Romano V, Porcelli F, et al. The bodies of two missing children in an enclosed underground environment. Forensic Sci Int 2011;207(1):e40–7.
4. Rowbotham SK, Blau S. Skeletal fractures resulting from fatal falls: a review of the literature. Forensic Sci Int 2016;266:582.e1–15.
5. Rozycki GS, Maull KI. Injuries sustained by falls. Arch Emerg Med 1991;8(4):245–52.
6. Auñón-Martín I, Doussoux PC, Baltasar JLL, Polentinos-Castro E, Mazzini JP, Erasun CR. Correlation between pattern and mechanism of injury of free fall. Strategies Trauma Limb Reconstr 2012;7(3):141–5.

7. Reynolds BM, Balsano NA, Reynolds FX. Falls from heights: a surgical experience of 200 consecutive cases. Ann Surg 1971;174(2):304–8.
8. Velmahos GC, Demetriades D, Theodorou D, Cornwell EE III, Belzberg H, Asensio J, et al. Patterns of injury in victims of urban free-falls. World J Surg 1997;21(8):816–21.
9. Scalea T, Goldstein A, Phillips T, Sclafani SJA, Panetta T, McAuley J, et al. An analysis of 161 falls from a height: the 'jumper syndrome'. J Trauma 1986;26(8):706–12.
10. Steedman DJ. Severity of free-fall injury. Injury 1989;20:259–61.
11. Richter D, Hahn MP, Ostermann PAW, Ekkernkamp A, Muhr G. Vertical deceleration injuries: a comparative study of the injury patterns of 101 patients after accidental and intentional high falls. Injury 1996;27(9):655–9.
12. Mathis RD, Levine SH, Phifer S. An analysis of accidental free falls from a height: the 'spring break' syndrome. J Trauma 1993;34(1):123–6.
13. Hohlrieder M, Eschertzhuber S, Schubert H, Zinnecker R, Mair P. Severity and pattern of injury in survivors of alpine fall accidents. High Alt Med Biol 2004;5(3):349–54.
14. Çetin G, Günay Y, Fincanci SK, Özdemir Kolusayin R. Suicides by jumping from Bosphorus Bridge in Istanbul. Forensic Sci Int 2001;116(2):157–62.
15. Lukas GM, Hutton JE, Lim RC, Mathewson C. Injuries sustained from high velocity impact with water: an experience from the Golden Gate Bridge. J Trauma 1981;21(8):612–8.
16. Perret G, Flomenbaum M, La Harpe R. Suicides by fall from height in Geneva, Switzerland, from 1991 to 2000. J Forensic Sci 2003;48(4):821–6.
17. Hanzlick R, Masterson K, Walker B. Suicide by jumping from high-rise hotels: Fulton County, Georgia, 1967-1986. Am J Forensic Med Pathol 1990;11(4):294–7.
18. Gill JR. Fatal descent from height in New York City. J Forensic Sci 2001;46(5):1132–7.
19. Li L, Smialek JE. The investigation of fatal falls and jumps from heights in Maryland (1987–1992). Am J Forensic Med Pathol 1994;15(4):295–9.
20. Goren S, Subasi M, Týrasci Y, Gurkan F. Fatal falls from heights in and around Diyarbakir, Turkey. Forensic Sci Int 2003;137(1):37–40.
21. Peng T-A, Lee C-C, Lin JC-C, Shun C-T, Shaw K-P, Weng TI. Fatal falls from height in Taiwan. J Forensic Sci 2014;59(4):978–82.
22. Obeid NR, Bryk DJ, Lee T, Hemmert KC, Frangos SG, Simon RJ, et al. Fatal falls in New York City: an autopsy analysis of injury patterns. Am J Forensic Med Pathol 2016;37(2):80–5.
23. Türk EE, Tsokos M. Pathologic features of fatal falls from height. Am J Forensic Med Pathol 2004;25(3):194–9.
24. Casali MB, Battistini A, Blandino A, Cattaneo C. The injury pattern in fatal suicidal falls from a height: an examination of 307 cases. Forensic Sci Int 2014;244:57–62.
25. Gulati D, Aggarwal AN, Kumar S, Agarwal A. Skeletal injuries following unintentional fall from height. Turkish J Trauma Emerg Surg 2012;18(2):141–6.
26. Teh J, Firth M, Sharma A, Wilson A, Reznek R, Chan O. Jumpers and fallers: a comparison of the distribution of skeletal injury. Clin Radiol 2003;58(6):482–6.
27. Abel SM, Ramsey S. Patterns of skeletal trauma in suicidal bridge jumpers: a retrospective study from the southeastern United States. Forensic Sci Int 2013;231:399.e1–5.
28. Venkatesh VT, Pradeep Kumar MV, Jagannatha SR, Radhika RH, Pushpalatha K. Pattern of skeletal injuries in cases of falls from a height. Med Sci Law 2007;47(4):330–4.
29. Petaros A, Slaus M, Coklo M, Sosa I, Cengija M, Bosnar A. Retrospective analysis of free-fall fractures with regard to height and cause of fall. Forensic Sci Int 2013;226:290–5.
30. Rowbotham SK. Low energy blunt force trauma – fatal falls. In: Blau S, Ranson D, O'Donnell C, editors. An atlas of skeletal trauma in medico-legal contexts. San Diego, CA: Academic Press, 2017;189–274.
31. Rowbotham SK, Blau S. The circumstances and characteristics of fatal falls in Victoria, Australia: a descriptive study. Aust J Forensic Sci 2017;49(4):403–20.
32. O'Donnell C. An image of sudden death: utility of routine post-mortem computed tomography scanning in medico-legal autopsy practice. Diagn Histopathol 2010;16(12):552–5.
33. Mickey RM, Greenland S. The impact of confounder selection criteria on effect estimation. Am J Epidemiol 1989;129(1):125–37.
34. Warner KG, Demling RH. The pathophysiology of free-fall injury. Ann Emerg Med 1986;15(9):1088–93.
35. Snyder RG. Human survivability of extreme impacts in free-fall. Oklahoma City, OK: Federal Aviation Agency, Civil Aeromedical Research Institute, 1963; Report No.: 63–15.
36. Tan S, Porter K. Free fall trauma. Trauma 2006;8(3):157–67.
37. Greenberg MI. Falls from heights. JACEP 1978;7(8):300–1.
38. Chao T-C, Lau G, Teo CE-S. Falls from a height: the pathology of trauma from vertical deceleration. In: Mason JK, Purdue BN, editors. The pathology of trauma. 3rd rev. edn. London, U.K.: Arnold; 2000;313–26.
39. Simonsen J. Injuries sustained from high-velocity impact with water after jumps from high bridges: a preliminary report of 10 cases. Am J Forensic Med Pathol 1983;4(2):139–42.
40. Christensen AM. The influence of behavior on freefall injury patterns: possible implications for forensic anthropological investigations. J Forensic Sci 2004;49(1):5–10.
41. Goonetilleke UKDA. Injuries caused by falls from heights. Med Sci Law 1980;20(4):262–75.
42. Lowenstein SR, Yaron M, Carrero R, Devereux D, Jacobs LM. Vertical trauma: injuries to patients who fall and land on their feet. Ann Emerg Med 1989;18(2):161–5.
43. Isbister ES, Roberts JA. Autokabalesis: a study of intentional vertical deceleration injuries. Injury 1992;23(2):119–22.
44. Lapostolle F, Gere C, Borron SW, Pétrovic T, Dallemagne F, Beruben A, et al. Prognostic factors in victims of falls from height. Crit Care Med 2005;33(6):1239–42.
45. İçer M, Güloğlu C, Orak M, Üstündağ M. Factors affecting mortality caused by falls from height. Ulusal Travma Acil Cerrahi Derg 2013;19(6):529–35.
46. Kohli A, Banerjee KK. Pattern of injuries in fatal falls from buildings. Med Sci Law 2006;46(4):335–41.
47. Lewis WS, Lee AB, Grantham SA. "Jumpers syndrome": the trauma of high free fall as seen at Harlem Hospital. J Trauma 1965;5(6):812–8.
48. Gupta SM, Chandra J, Dogra TD. Blunt force lesions related to the heights of a fall. Am J Forensic Med Pathol 1982;3(1):35–43.
49. Atanasijevic TC, Savic SN, Nikolic SD, Djokic VM. Frequency and severity of injuries in correlation with the height of fall. J Forensic Sci 2005;50(3):608–12.
50. Rowbotham SK, Blau S, Hislop-Jambrich J, Francis V. Skeletal trauma resulting from fatal low (≤3 m) free falls: an analysis of fracture patterns and morphologies. J Forensic Sci 2017. https://doi.org/10.1111/1556-4029.13701. Epub 2017 Nov 30.
51. Atanasijevic TC, Popovic VM, Nikolic SD. Characteristics of chest injury in falls from heights. Leg Med 2009;11:s315–7.
52. Galloway A. The lower extremity. In: Wedel VL, Galloway A, editors. Broken bones: anthropological analysis of blunt force trauma. 2nd rev. edn. Springfield, IL: Charles C. Thomas, 2014;245–308.
53. Rosen DH. Suicide survivors: a follow-up study of persons who survived jumping from the Golden Gate and San Francisco-Oakland Bay Bridges. West J Med 1975;122(4):289–94.
54. Kremer C, Racette S, Dionne C-A, Sauvageau A. Discrimination of falls and blows in blunt head trauma: systematic study of the hat brim line rule in relation to skull fractures. J Forensic Sci 2008;53(3):716–9.