An evaluation of the differences in paediatric skeletal trauma between fatal simple short falls and physical abuse blunt impact loads: An international multicentre pilot study

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Highlights

•Of forensic paediatric deaths, short falls comprised 0.1% and physical abuse 0.6%.

•Pilot findings suggest possible differences between short falls and physical abuse.

•Simple short falls resulted in simple linear neurocranial fractures.

•Physical abuse resulted in linear or complex skull fractures and postcranial trauma.

•Pilot data forms the foundation of the Registry of Paediatric Fatal Fractures (RPFF).

Abstract

In cases where a deceased child exhibits trauma as a result of a physical abuse blunt impact load, a parent/caregiver may provide a simple short fall (SSF) as the justification for that trauma. The skeletal fractures remain difficult to differentiate between a SSF and physical abuse however, as both are the result of a blunt impact load, and are therefore biomechanically alike, and the rare nature of these fatalities means only anecdotal research has been available to validate such claims. The aim of this pilot study was to investigate if there may be differences in the skeletal fracture patterns and types resulting from SSFs compared with those resulting from physical abuse blunt impacts. Paediatric (<10 years) cases of fatal SSFs (≤1.5 m) and physical abuse were collected from the Victorian Institute of Forensic Medicine (Australia), Institut Médico-Légal de Paris (France), University of Pretoria (South Africa) and Great Ormond Street Hospital (England). For each case the intrinsic and extrinsic variables were recorded from medico-legal reports and skeletal trauma was documented using post-mortem computed tomography scans and/or skeletal surveys. Three SSFs and 18 physical abuse cases were identified. Of the SSF cases, two exhibited fractures; both of which were simple linear neurocranial fractures. Comparatively, 12 of the physical abuse cases exhibited fractures and these were distributed across the skeleton; 58% located only in the skull, 17% only in the post-cranial and 25% located in both. Skull fracture types were single linear, multiple linear and comminuted. This pilot study suggests, anecdotally, there may be differences in the fracture patterns and types between blunt impact loads resulting from a SSF and physical abuse. This data will form the foundation of the Registry of Paediatric Fatal Fractures (RPFF) which, with further multicentre contributions, would allow this finding to be validated.

Keywords: Paediatric skeletal trauma; Blunt impact load; Physical abuse; Simple short fall; Medical imaging; Registry

1 INTRODUCTION

Differentiating the skeletal trauma that results from accidental simple short falls (SSF) (i.e., free fall of ≤ 1.5 m from a stationary position onto a hard surface) with those resulting from physical abuse (e.g., punched, kicked) remains a diagnostic dilemma in paediatric forensic medicine. Both blunt force trauma events are the result of an impact load; that is, either the moving body strikes a stationary object, typically SSF, or the body is struck by a moving object, typically physical abuse. As both events result in a blunt impact load, they are therefore biomechanically alike and thus the resulting skeletal injuries may be similar, making the blunt force trauma events difficult to differentiate.

In cases where a deceased child exhibits trauma as a result of physical abuse blunt impact loads, a parent/caregiver may provide a SSF as the justification for that trauma (e.g., [1], [2], [3]). Although studies have shown that fatal SSFs are very rare events [4], [5], post-mortem case series do exist [2], [6], [7] and biomechanical modelling, although not uniformly agreed upon, has validated their plausibility [8]. Thus, it is essential to accurately differentiate trauma that results from a fatal SSF with that resulting from physical abuse, as the consequences of an incorrect interpretation of the manner of injury (i.e., accident or abuse) may have significant health, welfare and justice implications for the deceased child and their family/caregiver. The ramifications of when the wrong diagnosis of the manner of trauma is made has been exemplified on an individual case level by Barnes et al. [8] and Conradi and Brissie [9], as well as in reviews of large-scale miscarriages of justice, including the 2007 Inquiry into Pediatric Forensic Pathology in Ontario [10].

Comprehensive understanding of the skeletal trauma resulting from blunt impact loads in physical abuse and SSFs has come from clinical, rather than post-mortem, contexts. Since fractures resulting from physical abuse were first noted by physician John Caffey in 1946 [11], extensive empirical research has documented diagnostic fracture patterns for suspected physical abuse [12], [13], [14], [15], [16], [17], [18], [19] and fracture pattern models to differentiate physical abuse from various causes of accidental trauma [20], [21], [22]. This research has provided a strong evidence base for the interpretation of non-fatal physical abuse by identifying the fractures which have a high specificity for abuse. These include: complex skull fractures, as well as fractures of the metaphyses, scapulae, ribs, and vertebrae; when fractures occur bilaterally and/or are varying ages, as well as subluxations [15], [21], [22], [23], [24]. Both Bilo et al. [25] and Kemp et al. [21] concluded that the trauma both blunt impact loads tended to have in common was linear fractures of the parietal bone, however they reiterated that no fracture on its own was diagnostic for abuse or accidental trauma. In cases of non-fatal SSFs, fracturing has shown to be a rare occurrence that may involve the skull, but that those fractures are not commonly associated with severe brain injury [26], [27], [28], [29]; further reiterating that, although a fracture may result, these injuries are typically not life-threatening. In the case of a skull fracture, these have typically been identified as simple linear or depressed [27], [28], [29], [30], [31]. Finite element modelling [32] and biomechanical experiments [33] have validated these findings; supporting the retrospective conclusions that SSFs are able to result in skull fractures and that these may be simple or multiple linear in type.

The skeletal injuries present in children who survive however, are not directly comparable to post-mortem cases. In clinical cases, the trauma is not typically life threatening and so may involve anatomical regions of the body that would not result in fatality, such as areas not associated with protecting vital organs (e.g., skull), or the severity of the trauma may have been less than what would have occurred in fatal cases. Subsequently, although clinical literature provides the foundational evidence base for blunt force trauma analysis in post-mortem contexts, its applications are limited.

In post-mortem contexts, the evidence base for the interpretation of skeletal trauma resulting from physical abuse blunt impact loads, although not as comprehensive as the clinical work, still provides some foundation. Research by Abel [34], Love et al. [35] and Baker [23], underpinned by anecdotal studies [36], [37] and epidemiological reviews [38], identified, not surprisingly, that there are no unique fracture patterns or types diagnostic of fatal blunt force physical abuse. Rather, all regions of the skeleton are susceptible to fracturing, with the skull, ribs and long bones being most prevalent, and that any type of fracture (e.g., complex, linear, spiral) may result as this is dependent on the nature of the abuse and the blunt implement used [23], [35]. It is important to note however, that these findings are in reference to blunt force trauma broadly (e.g., compression, tension, rotation, shearing and bending) and thus not all skeletal findings will be associated specifically with physical abuse impact loads.

In contrast, fatal SSFs have not been subject to empirical research. Due to the relative rarity of these events, only anecdotal case studies/series [2], [6], [7] have documented the skeletal trauma resulting from fatal SSFs. Subsequently, the skeletal trauma that is characteristic of this impact load remains unclear. From this anecdotal work, Plunkett [7] noted head injuries were associated with fatal SSFs, and that of the five SSF cases in his series, one had associated skull fractures, which involved the calvarium and were complex in type. Denton and Mileusnic [6] identified a linear skull fracture of the parietal bone, whilst Reiber [2] reported brain injuries with no associated skull fracture.

With a limited evidence base and many of the current findings unclear or non-substantiated, it remains difficult to differentiate the skeletal trauma resulting from fatal SSFs with fatal physical abuse blunt impact loads. The aim of this pilot study was to use a multicentre approach to identify if there were potential differences in the fracture patterns and types resulting from fatal SSFs and physical abuse blunt impact loads.

2 MATERIALS AND METHODS

Cases of paediatric (<10 years of age) fatal blunt impact loads resulting from SSFs (i.e., falls of ≤ 1.5 m from a stationary position onto a hard surface) and physical abuse were retrospectively collected from the databases of four medico-legal institutions. These institutions were the: Victorian Institute of Forensic Medicine (VIFM) (Melbourne, Australia); Institut Médico-Légal de Paris (IMLP) (Paris, France); Pretoria Medico-Legal Laboratory (PMLL), University of Pretoria (Pretoria, South Africa) and Great Ormond Street Hospital (GOSH) (London, England). Each database was retrospectively reviewed for paediatric deaths admitted for medico-legal investigation where the original notes suggested blunt force trauma may be the result of a SSF or physical abuse, and imaging data was available. Collectively, this comprised a sample of 132 deaths. For each death, the medico-legal files were reviewed to identify true cases of SSFs and physical abuse. These files comprised, where possible, circumstantial information from law enforcement, forensic pathology, forensic radiology and legal (i.e., coronial) findings. Deaths were included in the study when there was evidence of blunt impact trauma, established from the pathology and radiology findings, and contextual details of the traumatic event were provided and substantiated with police information and, in some cases, legal findings. Deaths were excluded from the study if the death was assumed or found to be natural (e.g., sudden infant death syndrome); if the circumstances were not provided, unclear or unsubstantiated; the blunt load was irrelevant, and if it was unclear if a SSF or physical abuse resulted in the blunt impact load. For select physical abuse cases where the details of precisely how the blunt force impact occurred were unclear, these deaths were still included if the associated medical and law enforcement investigation established the death as a homicide. Although there are several limitations that affect ‘ground truth’ when employing such a retrospective circumstantial model to establish the blunt force event, as detailed in the Discussion, this analysis of medical and contextual information remains one of the few suitable methods available for addressing trauma questions in forensic medicine and is accepted in the Choudhary et al. [39] consensus statement.

For each relevant death, intrinsic (i.e., age, sex, weight and height) and extrinsic (i.e., height of fall or, for physical abuse, the object used and number of impacts) variables were recorded from the associated medical, law enforcement and legal findings, where available. Skeletal trauma was analysed by retrospective review of full-body post-mortem computed tomography (PMCT) scans for the VIFM, PMLL and IMLP cases and from a combination of PMCT scans and radiographs for the GOSH cases (Table 1). Imaging was used as the preferred method for skeletal trauma analysis due to its high sensitivity and specificity for identifying skeletal fractures [40], [41], as well as its accessibility for retrospective research. For cases with PMCT scans, each skeletal element was reviewed in the axial, sagittal and coronal planes. Fracture patterns were documented per bone and fracture types were described using standard terminology (e.g., linear, depressed, comminuted). When present, ante-mortem skeletal trauma was recorded. The differentiation of ante-mortem from peri-mortem fractures was made from a combination of the PMCT images, plain film radiographs and the histology findings reported in the forensic pathology reports. Such a holistic approach follows recommended best practice for accurately identifying ante-mortem fractures [42], [43] and was utilised due to the complex nature of remodelling in that only histology could identify ante-mortem fractures that were very recent (e.g., few days old), whilst older fractures with clear evidence of bony remodelling were identifiable from imaging.

Skeletal trauma was assessed by one author (SKR). From each institution 30–50% of the cases included were randomly selected and cross-examined by forensic radiologists for quality assurance. Due to the study's small sample size, descriptive analyses comprising measures of frequency and Fisher's Exact tests were undertaken.

Ethical approval was obtained from the VIFM Research Advisory Committee (RAC011-18) and Ethics Committee (EC10-2018); the University of Pretoria Faculty of Health Sciences Research Ethics Committee (369/18), and University College London Institute of Child Health/GOSH Research

Table 1. Post-mortem CT specifications for each medico-legal institution.

	Years	Location of Imaging	CT scanner specifications	Multimodality image rendering software	Protocol for scanning paediatric cases
VIFM	2006–2009	VIFM	Toshiba Aquillion 16® (Helical 16 rows, typical tube voltage 120 kVp), 0.6–1 mm slice thickness.	Syngo.via (VB20A_HF05)	Routine for every case admitted to the VIFM.
	2009–2017	VIFM	SOMATOM® Definition Flash, Siemens Healthcare (Helical 128 rows, tube voltage 140 kVp). 0.5–0.7 mm slice thickness.	Syngo.via (VB20A_HF05)	
IMLP[a]	2014–2018	Centre Hospitalier Sainte-Anne	General Electric Lightspeed, 64-detector CT scanner, 120 kV, 0.6–2.5 mm slice thickness	Advantage Windows 4.6, GE Healthcare	Requested at discretion of the forensic pathologist.
PMLL	2011–2018	Steve Biko Academic Hospital	Siemens SOMATOM ® Sensation Cardiac 64. Full body scans: 3 mm × 3 mm thick cuts and 0.6 mm × 0.6 mm thin cuts for reconstructions. Head scan: head soft tissue 5 mm × 5 mm, axial Head bone 3 mm × 3 mm, axial thick cuts 1 mm × 0.5 mm thin cuts for reconstructions. Neck, Body and Leg scans: 2 mm x 2 mm thick cuts 1 mm × 0.5 mm thin cuts for reconstructions.	Enterprise Imaging, Diagnostic Desktop 8.0.1 SP12 AGFA Healthcare	Routine for all abuse/suspected abuse cases, and all sudden unexpected deaths. Imaging requested at discretion of the forensic pathologist.
GOSH	2010–2013	GOSH	Siemens SOMATOM® Definition (64 slice), 1 mm slice thickness	Syngo.via	Required for all cases with suspicious circumstances surrounding death.
	2014–2018	GOSH	Siemens SOMATOM FORCE® (364 helical; typical tube voltage 120 kV), 1 mm slice thickness.	Syngo.via	

[a]one IMLP case was reviewed from micro-computed tomography image photographs and autopsy photographs as the PMCT and radiographs were unavailable.

Ethics Committee (05/Q0508/96). Separate ethics approval from the IMLP was not required as the institution accepted the VIFM ethics approval under their existing memorandum of understanding.

3 RESULTS

A total of 132 deaths considered possible SSFs or physical abuse with associated imaging were available for review (Table 2). In total, 21 of those cases met the study inclusion criteria for either a fatal SSF (n = 3) or fatal physical abuse (n = 18) resulting from a blunt impact load (see Table 2). Of the 2, 911 total paediatric deaths admitted for medico-legal investigation, SSFs thus comprised an average of 0.1% of cases and physical abuse an average of 0.6% of cases. The remaining 111 deaths were excluded from the study. Of these, 36 were an irrelevant blunt force event or non-traumatic death; 19 were other types of blunt force physical abuse (e.g., compression, hyper-extension, shaking) or falls (e.g.,>1.5 m) and 27 had insufficient contextual details to establish if the case was a SSF or physical abuse. The remaining 29 were potentially relevant deaths, however case complexities or insufficient information meant that, for some cases of physical abuse it was not possible to differentiate an impact from other blunt forces, and in other cases it was not possible to differentiate a SSF from physical abuse (see Table 2).

Of the 21 cases included in the study, 9 (43%) were female and 12 (57%) male. Ages ranged from six days through to nine years old, with an average age of two years (Table 3). The cause of death was available in 19 cases and, of those, 89% (n = 17) were related to head injuries (see Table 3). For the physical abuse cases where cause of death was related to head injuries, those cases were thus considered cases of abusive head trauma (AHT) [39].

The circumstances resulting in the blunt impact loads were varied. The three SSFs comprised falls from heights of approximately one metre; fall from parents back, fall from parents' arms and fall from kitchen bench. None of the falls were independently witnessed. In one case it was reported the caregivers had, prior to the investigation, initially been arrested for abuse when they alleged the trauma was the result of a SSF. Physical abuse cases involved a variety of blunt implements comprising both the physical body of the abuser (e.g., hand – punch, foot – stomp) as well as objects

Table 2. Cases of relevance for the study across the four medico-legal institutions.

Empty Cell	Years imaging data was available	Number of child deaths (0–10 years) admitted	Yearly average	Deaths of possible relevance for review	Excluded Cases				Included Cases	
					Irrelevant case (i.e., accidental blunt force event/non-traumatic death)	Case reported as fall/physical abuse, however there was insufficient/unclear contextual details to confirm case suitable for study	Case was other type of blunt force physical abuse or fall	Possibly relevant case, however could not differentiate if blunt force abuse was 'impact' trauma or differentiate blunt force abuse from SSF due to insufficient information/ complexities of findings	Simple Short Fall	Physical Abuse
VIFM	2006–2017	1408	117	22	0	0	3	8	0	11
IMLP	2014–2018	139	28	14	3	1	4	4	0	2
PMLL	2011–2018	753	94	20	7	5	2	2	1	3
GOSH	2010–2018	611	68	76	26	21	10	15	2	2
Total		2911		132	36	27	19	29	3	18

(e.g., wrench). In nine cases the details of the physical abuse event were unsubstantiated or unclear, however the medical and investigative evidence concluded the injuries were attributed to blunt impact loads in the context of homicide and thus they were appropriate to include.

Table 3. Demographic and circumstantial detail by blunt force impact load.

Empty Cell		**Physical abuse (n = 18)**		**Simple short fall (n = 3)**	
		No.	**%**	**No.**	**%**
Sex	Males	10	56	2	67
Empty Cell	Females	8	44	1	33
Age (years)	0–3	15	83	3	100
Empty Cell	4–6	2	11	0	0
Empty Cell	7–9	1	6	0	0
Cause of Death	Related to head injury	13	72	2	67
Empty Cell	Related to head and chest/abdomen injuries	2	11	0	0
Empty Cell	Related to chest/abdomen injuries	2	11	0	0
Empty Cell	Unavailable[a]	1	67	1	33
Ante-mortem fractures	Present	9	50	0	0
CPR related rib fracture	Present	1	6	1	33

[a]autopsy was completed, however the pathology report was unavailable. Clinical notes, radiology reports and law enforcement summaries describe injuries as involving only the head (SSF case) and both head and extremities (physical abuse case).

Skeletal trauma occurred from two (67%) of the SSFs and 12 (67%) of the physical abuse blunt impact loads. A Fisher's Exact test showed no significant relationship between the presence and absence of fractures. Retrospective centralised radiological review of the imaging showed full agreement with the initial trauma analysis; no further fractures were identified. Cases of SSFs exhibited only skull fractures, whilst cases of physical abuse exhibited skull and post-cranial fractures; 58% (n = 7) located only in the skull, 17% (n = 2) only in the post-cranial and 25% (n = 3) located in both (Table 4, Fig. 1). A Fisher's Exact test showed this relationship was not significant. The distribution of the skull fractures between the two blunt impact loads differed. In cases of SSFs, fractures were localised to the neurocranium, whilst in cases of AHT fractures involved all aspects of the skull (see Table 4, Fig. 1). In the SSF cases with fractures, only a single skull bone was involved with each impact load, whilst in the AHT cases, fracturing involved more than one skull bone in 60% of the skull fracture cases.

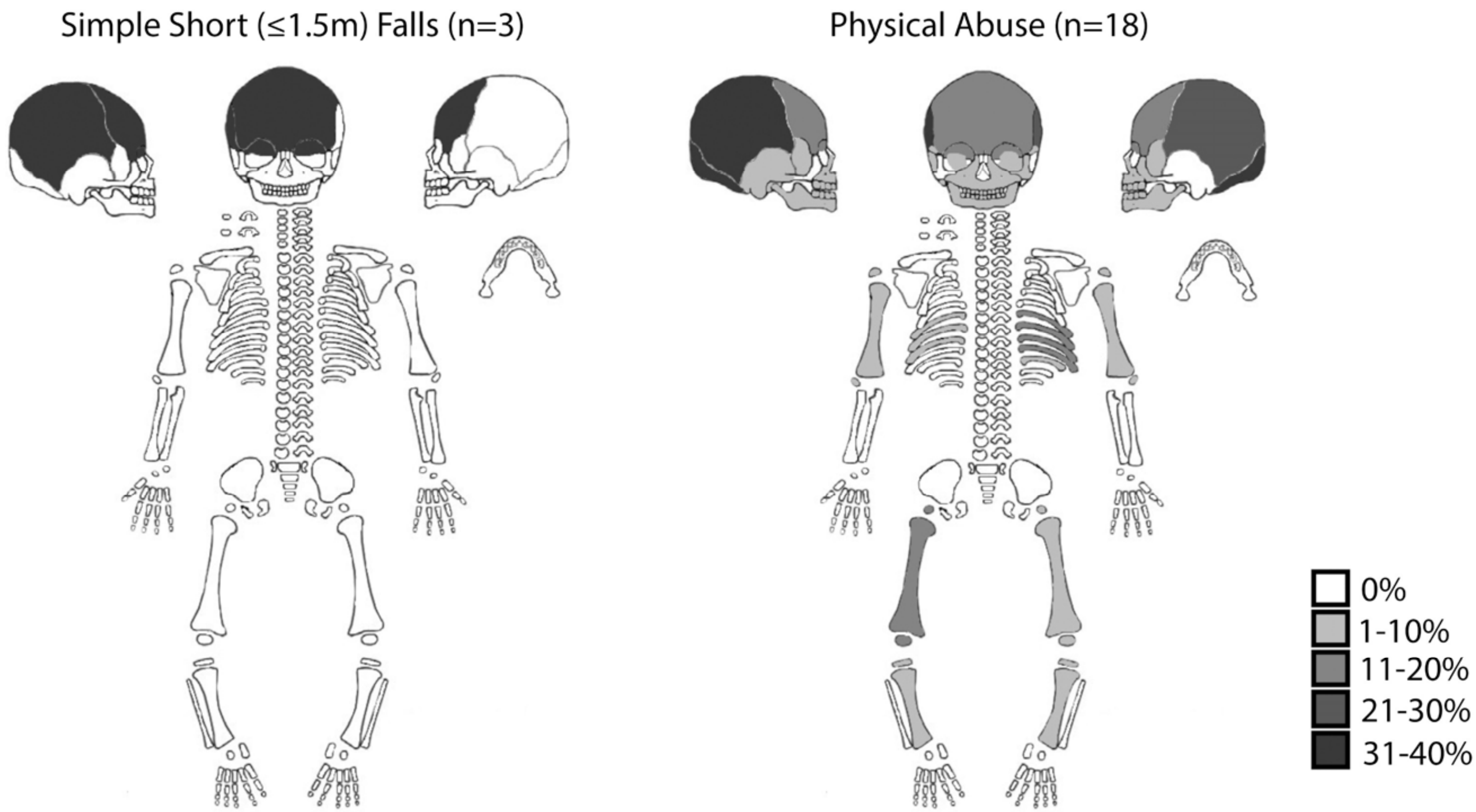

Fig 1. The frequency and distribution of fractures as related to the blunt impact load.

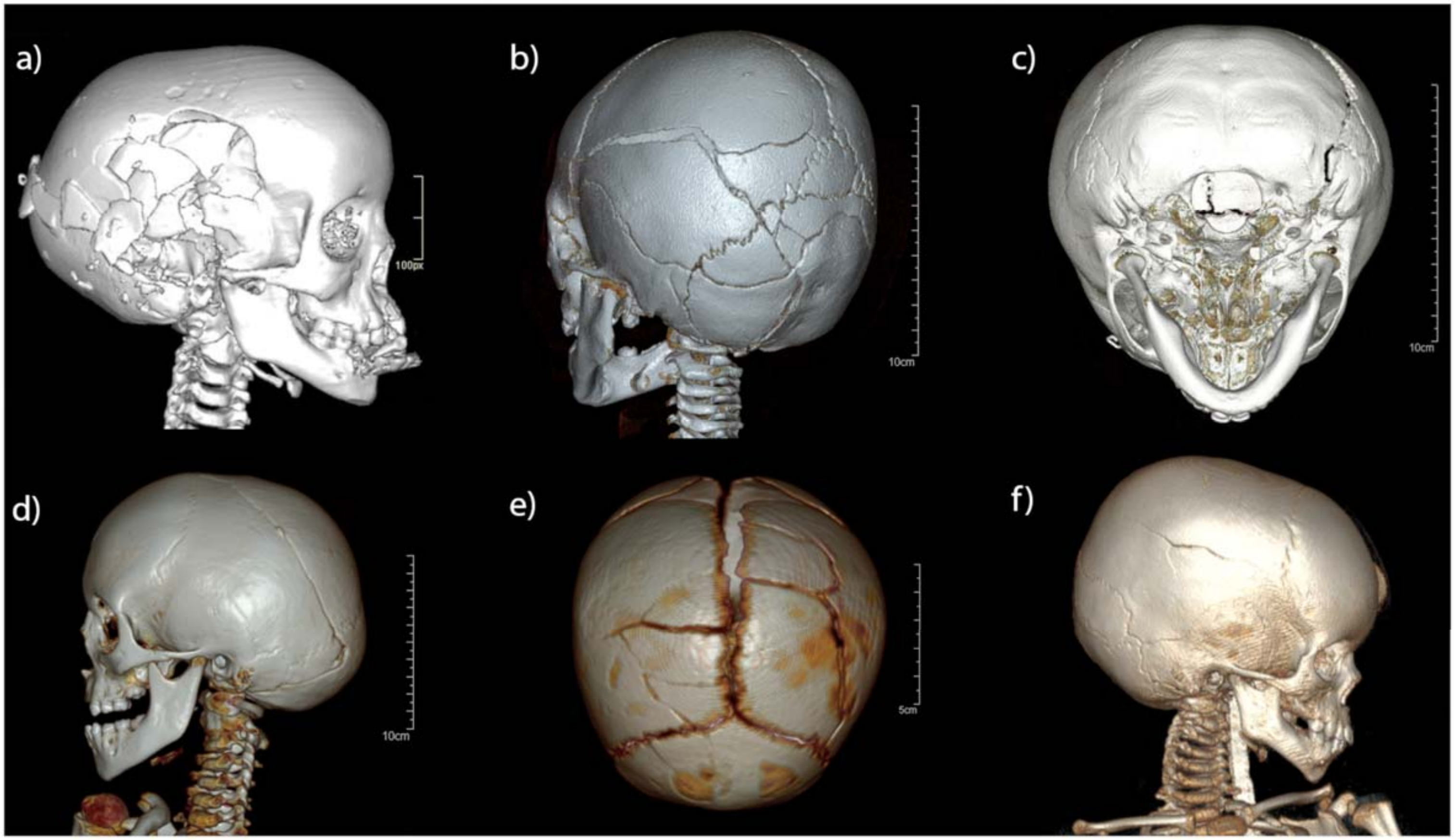

Fig 2. Volume rendered views of the skull showing examples of the different fractures resulting from blunt impact loads following physical abuse. a) Right lateral view showing displaced comminuted fractures; (b) Posterior oblique view showing comminuted fracturing; (c) Inferior view showing a simple linear fracture of the skull base; (d) Left lateral view showing multiple linear fractures with a displaced fragment of bone; (e) Superior view showing comminution with diastases; (f) Right lateral view showing multiple linear fractures.

Table 4. Skeletal elements fractured as a result of the blunt force impact loads by age group.

		Physical abuse (n = 18)				Simple short fall (n = 3)	
		0–3 years		4–10 years		0–3 years	
		No.	%	No.	%	No.	%
Skull	Frontal	1	5.56	1	5.56	1	33.33
	L parietal	3	16.67	1	5.56	0	0
	R parietal	5	27.78	1	5.56	1	33.33
	R temporal	0	0	1	5.56	0	0
	Occipital	6	33.33	1	5.56	0	0
	Sphenoid	0	0	1	5.56	0	0
	L maxilla	0	0	1	5.56	0	0
	R maxilla	0	0	1	5.56	0	0
	L zygomatic	0	0	1	5.56	0	0
	Maxillae dentition	0	0	1	5.56	0	0
	Mandible	0	0	1	5.56	0	0
	Mandibular dentition	0	0	1	5.56	0	0
Post-cranial	R 6–8th ribs	1	5.56	0	0	0	0
	R humerus	1	5.56	0	0	0	0
	R femur	2	11.11	0	0	0	0
	R tibia	1	5.56	0	0	0	0
	L 6–9th ribs	2	11.11	0	0	0	0
	L 10th rib	1	5.56	0	0	0	0
	L humerus	1	5.56	0	0	0	0
	L femur	1	5.56	0	0	0	0
	L tibia	1	5.56	0	0	0	0

The two cases of SSFs both exhibited a simple linear neurocranial fracture, whilst those resulting from AHT exhibited a range of neurocranial fractures comprising simple linear, multiple linear, comminuted and diastatic (Fig. 2). As detailed in Table 5, six cases involved a combination of these fractures. Of the three cases exhibiting diastases, two were the result of a linear fracture radiating through part of a suture and the third was a fracture of the zygo-temporal suture causing diastasis. A Fisher's Exact test showed no significant relationship between neurocranial fracture type and blunt force impact load. Post-cranially, fracture types exhibited as a result of physical abuse comprised full-thickness transverse and buckle fractures of ribs (anterior and/or posterior) and metaphyseal and spiral fractures of long bones.

Table 5. Neurocranial fracture type combinations in the AHT cases (n = 10).

Fracture combination	Number of cases
Single linear	2
Multiple linear	2
Single linear involving diastasis	1
Comminution + single linear + diastasis	1
Multiple linear + comminution	1
Multiple linear + comminution involving diastasis	2
Displaced fragment + multiple linear	1

Fractures unrelated to the peri-mortem blunt impact load were identified in 11 (52%) cases (see Table 3). One SSF and one physical abuse case had cardiopulmonary resuscitation (CPR) administered and both exhibited unilateral anterolateral buckle rib fractures consistent with those reported to result from CPR in infants [44]. Ante-mortem (i.e., remodelled) fractures were present in nine of the physical abuse cases and none of the SSF cases. Eight cases were in children under the age of three years old and fractures involved the skull (n = 3), ribs (n = 5) and long bones (n = 4). Variations in the development of callus formation indicated one previous physical abuse event in some cases, but multiple events in other cases. In three cases a single bone had been fractured ante-mortem, whilst in six cases multiple bones had been fractured.

4 DISCUSSION

Fatal blunt impact loads associated with SSFs and physical abuse have been reported to be rare events [4], [5], [45], [46]. Such an observation is well validated in this pilot study where, of all paediatric deaths reported to four medico-legal institutions (n = 2911), collectively only 0.1% of cases were attributed to fatal SSFs and 0.6% to fatal physical abuse blunt impact loads. Not only is this study the first to identify and validate how rare these medico-legal cases are, but in particular the very low prevalence of SSFs identified suggests that cases may be rarer than previously reported [39].

Given it is rare for a blunt impact SSF and physical abuse event to result in fatality, the sample size in this pilot study is expectedly small and, consequently, conclusions drawn may only be considered anecdotal. While it is inappropriate to draw firm conclusions from anecdotal data, at the simple descriptive level, this pilot study suggests there may be notable differences in the skeletal trauma resulting from a SSF with blunt impact physical abuse. Such a conclusion, however, requires sample augmentation to investigate significant associations before it may be considered valid.

Most blunt impact loads occurred in children three years old or younger. Although case series have generally found fatal physical abuse and SSFs occur in children under three years old [36], [37], [47], and thus some research has specifically focused on this age demographic [4], this study took a broader approach in reviewing cases under the age of ten years to validate this demographic assumption. In cases of fatal physical abuse, majority of children were under the age of three years, which may be in part attributed to their greater vulnerability [48], however such abuse events still occurred in children up to the age of nine years. Comparatively, fatal SSFs, although having been reported to occur in children over three years old [7], found that, similar to Hall et al. [47], they only occurred in infants and toddlers.

Ante-mortem trauma was only present in cases of physical abuse. The presence of ante-mortem fractures in children, almost all younger than three years old, has long been considered a 'hallmark' indicator for suspected physical abuse [49], [50]. While it is possible that children may be clumsy and potentially show evidence of ante-mortem trauma not the result of physical abuse, to date, the anecdotal case reports of SSFs have not reported associated ante-mortem fractures [6], [7]; a finding further supported by this study.

Brain injuries, regardless of the presence or absence of associated skull fractures, were the most prevalent cause of death for blunt impact loads resulting from both SSFs and physical abuse. This has been well documented in the literature with physical abuse studies frequently reporting brain injuries as the primary trauma requiring clinical care [12], [16], [51], to the extent that they are commonly the cause of fatality [37], [39]. Similarly, brain injuries, although rarely found in SSF clinical cases [26], [27], [28], have been documented in every fatal case [2], [6], [7], [47].

Skeletal trauma showed the same frequency between cases of physical abuse (67%) and SSFs (67%). Such fatal blunt impact loads, however, commonly leave no injuries to the skeleton. Therefore, the absence of skeletal trauma in no way negates the possibility that either a SSF or physical abuse event occurred. As evident in one SSF case, which resulted in a haematoma, haemorrhages and cerebral oedema, and six physical abuse cases, as well as fatal cases reported in the literature [7], [37], [38], even when injuries were so severe they resulted in fatality, it is not surprising to see an absence of skeletal trauma. This variation in fracturing is attributed to the complex interplay between bunt force intrinsic and extrinsic variables. Such variables include, but are not limited to, the: area of bone impacted; direction of impact; energy distributed through impact; shape and size of the blunt object; skeletal developmental stage and soft tissue thickness [52], [53], [54]..

4.1 Fracture Patterns

When skeletal trauma resulted, there were several differences in the location and distribution of those fractures between the two blunt impact loads. In cases of SSFs, fractures were localised to the skull, whilst in physical abuse cases there were three different trauma patterns identified: fractures only of the skull, fractures only of the postcranial skeleton, and fracturing of both the skull and postcranial regions. Although only anecdotal, this difference between fracture patterns adds strength to observations previously identified in the literature. Plunkett's [7] retrospective case series that included SSFs found that, in cases where fracturing occurred, they exclusively involved the skull. Whilst in cases of physical abuse, Love et al. [35] and Bilo et al. [25] identified that fractures may occur in any region of the skeleton, but that the nature of these events resulting in fatality, typically means fracturing involves the skull; a pattern consistent with that seen in this pilot study.

As skeletal trauma resulting from both fatal blunt impact loads typically involves the skull, fracture distribution in this region is of particular interest. In SSFs, fractures were present only to the neurocranium and, more precisely, the anatomical region above the hat brim line (HBL) (as defined in Kremer et al. [55]); a fracture pattern in complete contrast to that seen in adults who experienced fatal falls from the same height [56]. Hajiaghamemar et al.'s [57] finite element models identified that a variety of neurocranial bones may fracture in a SSF, but that there is a greater frequency of parietal bone fracturing. This has been supported by biomechanical simulations by Weber [33], [58], who dropped infant cadavers from a short height onto different surfaces and found that, on impact, the parietal bone was the most fractured bone. Weber [58] suggested that this susceptibility to fracturing may be, in part, because the parietal bone only comprises a single thin layer without diploe at this early developmental stage and thus has less resistance to force.

In contrast, skull fractures resulting from AHT were not isolated to the neurocranial area above the HBL. Rather, fractures were found to occur, fairly equally, to all bones of the neurocranium (i.e., the anatomical regions above, within and below the HBL); a fracture distribution similar to that seen in blunt impact load assaults on adults [55], [59]. Although there was greater frequency of fracturing to the neurocranium, as also reported by Love et al. [35], with the parietal bone again tending to be one of the most commonly reported bones to fracture [21], [25], [60], the nature of abuse events are so variable that any and all aspects of the skull may be susceptible to blunt impact loads.

In the cases of SSFs, fracturing only involved a single skull bone, whilst in many AHT cases skull fractures involved more than one bone. The fracturing of only a single bone in the SSFs may indicate that the velocity in such falls was low and thus the magnitude of force distributed to the bone was insufficient for fractures to radiate across suture lines. Further, in falls there is only a single point of impact with the blunt surface and therefore, injuries are only to one plane of the body, with fracturing to the skeletal element typically being in that plane. In contrast, the variable nature of AHT events means that, in some cases, the force associated with the impact would exhibit magnitudes sufficient for fractures to radiate across sutures, and fractures may be sustained in multiples planes of the body (i.e., multiple bones) in cases where several impacts were distributed.

4.2 Fracture Types

The types of skull fractures resulting from SSFs and AHT differed. Only simple linear fractures resulted from SSFs, whilst a myriad of fracture types resulted from physical abuse. How bone responds to blunt loads, and thus fractures, is dependent on several extrinsic and intrinsic variables; one key variable being the shape of the object impacting with the body [61], [62]. Linear skull fractures typically result from contact with a large flat object where the impact of the force is distributed over a relatively large area [25]. In the case of SSFs, such fracture morphology is the only expected type of fracture, if fractures were present at all, given the individual is typically impacting a relatively hard, flat surface (i.e., floor). In this pilot study, only simple linear fractures of the skull were found to result from SSFs; indicating impact with a broad/flat surface as would be expected for a fall onto the floor. Denton and Mileusnic [6] similarly found in their post-mortem case of a SSF that fracturing of the skull was simple linear. Clinically, Hobbs [63] and Powell et al. [30] have reported simple linear fractures to commonly result from accidental blunt force events, of which a portion were short falls. However, this is not without controversy in the literature. Studies have reported fracture types other than simple linear to result from SSFs. In a clinical case, Wheeler and Shope [64] reported a depressed skull fracture as a result of the shape of the object the infant impacted, whilst in post-mortem contexts, Plunkett [7] reported a case with complex fracturing from a fall of 0.6 m onto compacted soil.

In contrast, diversity in fracture types, ranging from simple linear to comminuted, resulted from fatal AHT. Such variety was expected given the fracture morphology is dependent on a suite of intrinsic and extrinsic variables and is representative of the shape of the object impacting the bone. Such objects may be anything from a broad flat object (e.g., frying pan), which may produce linear fractures like those seen in SSFs, to any object of varying shape and weight and thus result in an infinite list of fracture morphologies. Similarly, Abel [34], Hobbs [63], Carty [15] and Meservy et al. [65] also identified a variety of fractures that may result from AHT, including simple and multiple linear, complex, bilateral, depressed, comminuted and fractures crossing sutures; furthering highlighting that no one fracture type is characteristic of this blunt impact event.

Post-cranially, the variety of fracture types identified in this study is again attributed to the intrinsic and extrinsic variables and nature of the assault. These fractures comprised transverse and buckle fractures of the ribs (anterior and/or posterior) and long bone metaphyseal and spiral fractures; all of which have been well documented to be ‘hallmark’ indicators of abusive treatment [23], [34], [66]. As several of these post-cranial fractures are not possible to result from direct impact, they reinforce that, although the fatal event was blunt impact, in these assaults a variety of blunt forces may be involved.

Fracture types identified in this pilot study further strengthen the evidence base that, whilst different types of fractures may be seen to all aspects of the skeleton in cases of physical abuse blunt impact loads, typically linear fractures of the skull result from SSFs. As the small sample size limits interpretation, it may be hypothesised only that, if the fracture pattern and type present is a simple linear fracture of the neurocranium, the blunt impact load may be either a SSF or physical abuse (i.e., AHT); however if the fracture pattern and type is anything other than a simple linear fracture of the neurocranium, it may be considered more suspicious of physical abuse.

4.3 Limitations

The most significant limitation with this pilot study was not attaining a sample size appropriate for predictive modelling. Such a limitation may be attributed to the quality of available contextual information, which subsequently also introduces selection bias concerns, and the nature of these deaths being rare events.

The quality and quantity of contextual information is essential for accurate trauma interpretation [67]. As evident in this pilot study, the absence of contextual information for almost half the sample size, meant it was not possible to interpret trauma in those cases and thus they were excluded. This hindered the drawing of conclusions beyond anecdotal and illustrates how complex and difficult the availability of accurate and complete information is for the post-mortem examination. Such difficulties may largely be attributed to the suspicious nature of these deaths. Physical abuse cases, that is homicides, are often complex to interpret as the circumstantial information and witness statements are questionable, thus making these types of cases significantly more multifaceted than accidental events where witness information is more reliably regarded. Similarly, for cases of fatal SSFs, there are rarely reliable independent witness statements to support the circumstances, unlike other types of accidental falls e.g., [68]. Additional complexity occurs in that all information provided in a medico-legal death investigation, including legal findings, may only be considered circumstantial. The nature of such retrospective reviews relying on circumstantial information, where conclusions made on first principles are used as ‘ground truth’, thus supporting assumptions and not evidence, ensures the reliability of the information associated with these cases is limited.

Such limitations also introduce selection bias concerns. Although there is no bias associated with accurately capturing all cases of fatal SSFs and physical abuse, as medico-legal institutions are responsible for investigating all unexplained and unnatural deaths and these types of deaths would have initially presented as unnatural and thus required forensic examination, there are other bias concerns. By only including deaths that met the strict study inclusion criteria, selection bias was introduced in that potentially not all fatal SSFs and physical abuse blunt impact cases were included. As detailed in Table 2, there was potentially a further 56 cases that may have been relevant for this study. It was not possible to validate if these cases were appropriate for inclusion however, because the review of medical data did not reveal there was evidence of impact (e.g., bruising or fracturing) in some cases, and in other cases the contextual information did not exist, or the details were unclear, around how that impact occurred. As such, by utilising only the 21 cases that met the inclusion criteria, the final data set has likely resulted in an underestimate of the true number of SSF and physical abuse cases admitted to medico-legal institutions. The nature of observational retrospective research however, means it is not possible to adjust for that selection bias.

The issue with high numbers of undetermined/unclear causes of trauma is not unique to these medico-legal institutions. Soto Martinez et al. [69] reported in the Injury Infant Database (IID), from the Harris County Institute of Forensic Sciences, that 44% of their paediatric cases had an undetermined manner of death, even when data was collected prospectively for the purpose of research. Further, like most of the information provided by medico-legal institutions involved in this study, the IID was also limited by associated contextual information as they were not accounting for legal findings, rather only the circumstantial information provided at the initial stages of an investigation. Such a deficit further reinforces the international need for improved collaboration between legal findings and the information fed back into the forensic medical system. Whilst such an approach brings contextual bias challenges to medico-legal practice [70], it is only through that holistic approach that case numbers will become sufficient to address these types of uncommon and complex paediatric fatalities.

The second limitation contributing to the small sample size is the low prevalence of fatalities associated with accidental and abusive paediatric trauma. As evident in this pilot study, across four institutions with a combined total of 2911 reportable paediatric deaths, only 21 deaths met the inclusion criteria. Similarly, the IID found trauma was rare with 10% of deaths attributed to trauma broadly [69], of which it may be hypothesised only a small proportion would have been blunt impact loads specifically. Further, most post-mortem research for fatal physical abuse [36], [37] and especially SSFs [2], [6], [7] have presented small sample sizes that resulted only in anecdotal conclusions.

4.4 The Registry of Paediatric Fatal Fractures (RPFF)

In order to move beyond anecdotal findings, a sufficient sample size to infer meaningful statistical analyses is required to provide an evidence base to develop accurate and reliable validated diagnostic models for fracture patterns and types. Kent et al. [71] calculated that an appropriate sample size to develop robust predictive models would be a minimum of 400 cases. As no one medico-legal institution has such a sample size of these types of deaths, attaining such a sample is only possible through multicentre collaborations on an international scale.

The SSF and physical abuse data collected from this pilot study (n = 21) forms the foundation of the Registry of Paediatric Fatal Fractures (RPFF). The registry, archived with the VIFM and accessible through relevant ethics approvals, is available to medico-legal researchers to augment with additional cases of fatal paediatric trauma and to utilise the cases already archived for research. The need for large-scale collaborative multicentre approaches to address complex and rare medico-legal issues for abused infants and children has already been successfully undertaken in clinical contexts by Hymel et al. [72], Berger et al. [73] and Pierce et al. [74], however this has not yet been undertaken in post-mortem contexts. Augmentation of the blunt impact load cases in the RPFF will, over time, allow for sufficient investigation of these complex post-mortem paediatric medico-legal questions that are currently underpinned by a weak evidence base.

5 CONCLUSION

Findings of this pilot study show, for the first time, how rare SSFs and blunt impact physical abuse events are in post-mortem contexts. Although these fatalities are rare events and thus the sample size of this pilot study was small, anecdotal findings suggest there may be notable differences in the fracture patterns and types between blunt impact loads resulting from a SSF and physical abuse. When fracturing did occur, SSFs resulted in simple linear neurocranial fractures, whereas physical abuse resulted in linear or complex skull fractures as well as fractures of the postcranial skeleton. This observation, whilst further strengthening the evidence base, remains only anecdotal however, and thus an increased sample size through the augmentation of cases to the RPFF, would allow such a finding to be validated.

CRediT authorship contribution statement

Samantha K. Rowbotham: Conceptualization, Methodology, Investigation, Resources, Data curation, Writing - original draft, Visualization, Funding acquisition. **Ryan Blumenthal:** Investigation, Resources, Writing - review & editing. **Tania Delabarde:** Investigation, Resources, Writing - review & editing. **Laurence Legrand:** Validation, Resources, Writing - review & editing. **Elizabeth van der Walt:** Validation, Resources, Writing - review & editing. **Tom Sutherland:** Validation, Resources, Writing - review & editing. **Zarina Lockhat:** Validation, Resources, Writing - review & editing. **Owen J. Arthurs:** Investigation, Validation, Resources, Writing - review & editing, Supervision.

Conflict of interest

The authors declare that they have no known conflicts of interest.

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REFERENCES

1. S.M. John, P. Jones, P. Kelly, A. Vincent. Fatal pediatric head injuries: a 20-year review of cases through the Auckland Coroner's Office. Am. J. Forensic Med. Pathol., 34 (2013), pp. 277-282
2. G.D. Reiber. Fatal falls in childhood: how far must children fall to sustain fatal head injury? Report of cases and review of the literature. Am. J. Forensic Med. Pathol., 14 (3) (1993), pp. 201-207
3. D.L. Chadwick, S. Chin, C. Salerno, J. Landsverk, L. Kitchen. Deaths from falls in children: how far is fatal? J. Trauma, 31 (10) (1991), pp. 1353-1355
4. J.P. Ehsani, J.E. Ibrahim, L. Bugeja, S. Cordner. The role of epidemiology in determining if a simple short fall can cause fatal head injury in an nfant: a subject review and reflection. Am. J. Forensic Med. Pathol., 31 (2010), pp. 287-298
5. D.L. Chadwick, G. Bertocci, E. Castillo, L. Frasier, E. Guenther, K. Hansen, B. Herman, H.F. Krous. Annual risk of death resulting from short falls among young children: less than 1 in 1 million. Pediatrics, 121 (6) (2008), pp. 1213-1224
6. S. Denton, D. Mileusnic. Delayed sudden death in an infant following an accidental fall: a case report with review of the literature. Am. J. Forensic Med. Pathol., 24 (4) (2003), pp. 371-376
7. J. Plunkett. Fatal pediatric head injuries caused by short-distance falls. Am. J. Forensic Med. Pathol., 22 (1) (2001), pp. 1-12
8. P.D. Barnes, M.V. Krasnokutsky, K.L. Monson, J. Ophoven. Traumatic spinal cord injury: accidental versus nonaccidental injury. Semin. Pediatr. Neurol., 15 (4) (2008), pp. 178-184
9. S. Conradi, R. Brissie. Battered child syndrome in a four year old with previous diagnosis of Reye's syndrome. Forensic Sci. Int., 30 (1986), pp. 195-203
10. S.T. Gouge, Inquiry Into Pediatric Frorensic Pathology in Ontario: Report. Ontario Ministry of the Attorney General. 〈http://www.attorneygeneral.jus.gov.on.ca/inquiries/goudge/report/index.html〉. (Accessed 4 April 2020).
11. J. Caffey. Multiple fractures in the long bones of infants suffering from chronic subdural hematoma. Radiology, 194 (1946), pp. 163-173
12. A. Ward, J.A. Iocono, S. Brown, P. Ashley, J.M. Draus. Non-accidental trauma injury patterns and outcomes: a single institutional experience. Am. Surg., 81 (2015), pp. 835-838
13. R.T. Loder, C. Bookout. Fracture patterns in battered children. J. Orthop. Trauma, 5 (4) (1991), pp. 428-433
14. S.L. Swoboda, K.W. Feldman. Skeletal trauma in child abuse. Pediatr. Ann., 42 (11) (2013), pp. 236-243
15. H.M.L. Carty. Fractures caused by child abuse. J. Bone Jt. Surg., 75-B (6) (1993), pp. 849-857 [Br.]
16. A.K. Butlinski, W.W. Butt. The characteristics, pattern of injury and outcome of children admitted to a paediatric intensive care unit following an inflicted injury. Crit. Care Resusc., 19 (2017), pp. 23-28
17. J. Krishnan, P.J. Barbour, B.K. Foster. Patterns of osseous injuries and psychosocial factors affecting victims of child abuse. ANZ J. Surg., 60 (1990), pp. 447-450

18. I. Barber, J.M. Perez-Rossello, C.R. Wilson, P.K. Kleinman. The yield of high-detail radiographic skeletal surveys in suspected infant abuse. Pediatr. Radiol., 45 (2015), pp. 69-80

19. R.R. van Rijn, T. Sieswerda-Hoogendoorn. Educational paper: imaging child abuse: the bare bones. Eur. J. Pediatrics, 171 (2012), pp. 215-224

20. P. Worlock, M. Stower, P. Barbor. Patterns of fractures in accidental and nonaccidental injury in children: a comparative study. Br. Med. J., 293 (1986), pp. 100-102

21. A.M. Kemp, F. Dunstan, S. Harrison, S. Morris, M. Mann, K. Rolfe, S. Datta, D. Phillip Thomas, J.R. Sibert, S. Maguire. Patterns of skeletal fractures in child abuse: systematic review. Br. Med. J., 337 (2008), pp. 859-862

22. S.J. Piteau, M.G.K. Ward, N.J. Borrowman, A.C. Plint. Clinical and radiographic characteristics associated with abusive and nonabusive head trauma: a systematic review. Pediatrics, 130 (2) (2012), pp. 315-323

23. A.M. Baker. Evaluation of pediatric fractures at autopsy. K.A. Collins, R. Byard (Eds.), Forensic Pathology of Infancy and Childhood, Springer, New York (2014), pp. 339-374

24. M. Panuel, K. Chaumoitre, P. Petit, J.-L. Jouve. Skeletal injuries. C. Rey-Salmon, C. Adamsbaum (Eds.), Child Abuse: Diagnostic and Forensic Considerations, Springer International, Cham, Switzerland (2018), pp. 77-103

25. R.A.C. Bilo, S.G.F. Robben, R.R. van Rijn. Forensic Aspects of Pediatric Fractures: Differentiating Accidental Trauma from Child Abuse. Springer, Berlin (2010)

26. T.J. Lyons, R. Kim Oates. Falling out of bed: a relatively benign occurrence. Pediatrics, 92 (1993), pp. 125-127

27. C.A. Tarantino, M. Denise Dowd, T.C. Murdock. Short vertical falls in infants. Pediatr. Emerg. Care, 15 (1999), pp. 5-8

28. R.A. Williams. Injuries in infants and small children resulting from witnessed and corroborated free falls. J. Trauma, 31 (1991), pp. 1350-1352

29. C. Ruddick, M.W. Platt, C. Lazaro. Head trauma outcomes of verifiable falls in newborn babies. Arch. Dis. Child. Fetal Neonatal Ed., 95 (2010), pp. F144-F145

30. E.C. Powell, S.M. Atabaki, S. Wootton-Gorges, D. Wisner, P. Mahajan, T. Glass, M. Miskin, R.M. Stanley, E. Jacobs, P.S. Dayan, J.F. Holmes, N. Kuppermann. Isolated linear skull fractures in children with blunt head trauma. Pediatrics, 135 (4) (2015), pp. e851-e857

31. D.J. Kahn, P.D. Fisher, D.A. Hertzler. Variation in management of in-hospital newborn falls: a single-center experience. J. Neurosurg. Pediatr., 20 (2) (2017), pp. 176-182

32. X. Li, H. Sandler, S. Kleiven. Infant skull fractures: accident or abuse? Evidences from biomechanical analysis using finite element head models. Forensic Sci. Int., 294 (2019), pp. 173-182

33. W. Weber. Experimental studies of skull fractures in infants. Z. Rechtsmed., 92 (1984), pp. 87-94

34. S.M. Abel. Non-accidental skeletal trauma. A.H. Ross, S.M. Abel (Eds.), The Juvenile Skeleton in Forensic Abuse Investigations, Humana Press, Totowa (2011), pp. 61-77

35. J.C. Love, S.M. Derrick, J.M. Wiersema. Skeletal Atlas of Child Abuse. Humana Press, New York (2011)

36. S. Blau, D.L. Ranson, C. O'Donnell. An Atlas of Skeletal Trauma in Medico-Legal Contexts. Academic Press, San Diego (2018)

37. A.L.M. Kauppi, T. Vanamo, K. Karkola, J. Merikanto. Fatal child abuse: a study of 13 cases of continuous abuse. Ment. Illn., 4 (2012), pp. 5-9

38. A.H. Ross, S.M. Abel, D. Radisch. Pattern of injury in child fatalities resulting from child abuse. Forensic Sci. Int., 188 (2009), pp. 99-102

39. A.K. Choudhary, S. Servaes, T.L. Slovis, V.J. Palusci, G.L. Hedlund, S.K. Narang, J.A. Moreno, M.S. Dias, C.W. Christian, M.D. Nelson, V.M. Silvera, S. Palasis, M. Raissaki, A. Rossi, A.C. Offiah. Consensus statement on abusive head trauma in infants and young children. Pediatr. Radiol., 48 (2018), pp. 1048-1065

40. C. Cattaneo, E. Marinelli, A. Di Giancamillo, M. Di Giancamillo, O. Travetti, L. Vigano, P. Poppa, D. Porta, A. Gentilomo, M. Grandi. Sensitivity of autopsy and radiological examination in detecting bone fractures in an animal model: implications for the assessment of fatal child physical abuse. Forensic Sci. Int., 164 (2006), pp. 131-137

41. M.H. Mulroy, A.M. Loyd, D.P. Frush, T.G. Verla, B.S. Myers, C.R. Bass. Evaluation of pediatric skull fracture imaging techniques. Forensic Sci. Int., 214 (2012), pp. 167-172

42. A. Cappella, H.H. de Boer, P. Cammilli, D. De Angelis, C. Messina, L.M. Sconfienza, F. Sardanelli, C. Sforza, C. Cattaneo. Histologic and radiological analysis on bone fractures: estimation of posttraumatic survival time in skeletal trauma. Forensic Sci. Int., 302 (2019), Article 109909

43. T. Delabarde, M. Reynolds, M. Decourcelle, F. Pascaretti-Grizon, B. Ludes. Skull fractures in forensic putrefied/ skeletonised cases: the challenge of estimating the post-traumatic interval. Morphologie, 104 (2020), pp. 27-37

44. D. Dolinak. Rib fractures in infants due to cardiopulmonary resuscitation efforts. Am. J. Forensic Med. Pathol., 28 (2007), pp. 107-110

45. C. Jenny, R. Isaac. The relation between child death and child maltreatment. Arch. Dis. Child., 91 (3) (2006), pp. 265-269

46. K.D. Browne, M.A. Lynch. The nature and extent of child homicide and fatal abuse. Child Abus. Rev., 4 (1995), pp. 309-316

47. J.R. Hall, H.M. Reyes, M. Horvat, J.L. Meller, R. Stein. The mortality of childhood falls. J. Trauma, 29 (1989), pp. 1273-1275

48. D. DePanfilis, M.K. Salus, A Coordinated Response to Child Abuse and Neglect: A Basic Manual. Report, US Department of Health and Human Services, National Center on Child Abuse and Neglect, Washington, 1992.

49. P.K. Kleinman. Skeletal trauma: general considerations. P.K. Kleinman (Ed.), Diagnostic Imaging of Child Abuse, Mosby Inc., St Louis (1998), pp. 9-10

50. C.J. Hobbs, H.G.I. Hanks, J.M. Wynne. Child Abuse and Neglect: A Clinician's Handbook. Churchill Livingstone, Edinburgh (1993)

51. D.M. Rubin, C.W. Christian, L.T. Bilaniuk, K.A. Zazyczny, D.R. Durbin. Occult head injury in high-risk abused infants. Pediatrics, 111 (2003), pp. 1382-1386

52. L. Zephro, A. Galloway. The biomechanics of fracture production. V. Wedel, A. Galloway (Eds.), Broken Bones: Anthropological Anlysis of Blunt Force Trauma (2nd ed.), Charles C Thomas, Springfield, Illinois (2014), pp. 33-46

53. A.M. Kroman, S.A. Symes. Investigation of skeletal trauma. E.A. DiGangi, M.K. Moore (Eds.), Research Methods in Human Skeletal Biology, Academic Press, London (2012), pp. 219-239

54. N. Özkaya, D. Leger, D. Goldsheyder, M. Nordin. Fundamentals of Biomechanics: Equilibrium, Motion, and Deformation (4th ed.), Springer International Publishing, Switzerland (2017)

55. C. Kremer, S. Racette, C.-A. Dionne, A. Sauvageau. Discrimination of falls and blows in blunt head trauma: systematic study of the hat brim line rule in relation to skull fractures. J. Sci., 53 (3) (2008), pp. 716-719

56. S.K. Rowbotham, S. Blau, J. Hislop-Jambrich, V. Francis. Skeletal trauma resulting from fatal low (≤ 3 m) free falls: an analysis of fracture patterns and morphologies. J. Forensic Sci., 63 (2018), pp. 1010-1020

57. M. Hajiaghamemar, I.S. Lan, C.W. Christian, B. Coats, S.S. Margulies. Infant skull fracture risk for low height falls. Int. J. Leg. Med., 133 (2019), pp. 847-862

58. W. Weber. Biomechanical fragility of the infant skull. J. Leg. Med., 94 (1985), pp. 93-101

59. T. Lefévre, J.-C. Alvarez, G.L. de la Grandmaison. Discriminating factors in fatal blunt trauma from low level falls and homicide. Sci. Med. Pathol., 11 (2015), pp. 152-161

60. J.M. Leventhal, S.A. Thomas, N.S. Rosenfield, R.I. Markowitz. Fractures in young children: distinguishing child abuse from unintentional injuries. Am. J. Dis. Child., 147 (1993), pp. 87-92

61. A. Galloway, S. Symes, W.D. Haglund, D.L. France. The role of forensic anthropology in trauma analysis. A. Galloway (Ed.), Broken Bones: Anthropological Analysis of Blunt Force Trauma, Charles C. Thomas, Springfield (1999), pp. 5-31

62. J.C. Love. Neurocranial fractures. N.V. Passalacqua, C.W. Rainwater (Eds.), Skeletal Trauma Analysis: Case Studies in Context, John Wiley and Sons, Hoboken (2015), pp. 130-146

63. C.J. Hobbs. Skull fracture and the diagnosis of abuse. Arch. Dis. Child., 59 (1984), pp. 246-252

64. D.S. Wheeler, T.R. Shope. Depressed skull fracture in a 7-month-old who fell from bed.Pediatrics, 100 (1997), pp. 1033-1034

65. C.J. Meservy, R. Towbin, R.L. McLaurin, P.A. Myers, W. Ball. Radiographic characteristics of skull fractures resulting from child abuse. Am. J. Roentgenol., 149 (1987), pp. 173-175

66. I. Barber, P.K. Kleinman. Imaging of skeletal injuries associated with abusive head trauma. Pediatr. Radiol., 44 (2014), pp. s613-s620

67. S. Blau. How traumatic: a review of the role of the forensic anthropologist in the examination and interpretation of skeletal trauma. Aust. J. Forensic Sci., 49 (2017), pp. 261-280

68. S.K. Rowbotham, S. Blau, J. Hislop-Jambrich, V. Francis. Fatal falls involving stairs: an anthropological analysis of skeletal trauma. Forensic Sci. Med. Pathol., 14 (2018), pp. 152-162

69. M.E. Soto Martinez, J.C. Love, D.C. Pinto, J.M. Wiersema, S.M. Derrick, A. Bachim, C. Greeley, M. Donaruma-Kwoh, V.T.T. Truong, S. Gao, C.M. Crowder. The infant injury database: a tool for the study of injury patterns in medicolegal investigations of child abuse. J. Forensic Sci., 64 (2019), pp. 1622-1632

70. S. Nakhaeizadeh, I. Hanson, N. Dozzi. The power of contextual effects in forensic anthropology: a study of biasability in the visual interpretations of trauma analysis on skeletal remains. J. Forensic Sci., 59 (2014), pp. 1177-1183

71. P. Kent, E. Boyle, J.L. Keating, H.B. Albert, J. Hartvigsen. Four hundred or more participants needed for stable contingency table estimates of clinical prediction rule performance. J. Clin. Epidemiol., 82 (2017), pp. 137-148

72. K.P. Hymel, V. Armijo-Garcia, R. Foster, T.N. Frazier, M. Stoiko, L.M. Christie, N.S. Harper, K. Weeks, C.L. Carroll, P. Hyden, A. Sirotnak, E. Truemper, A.E. Ornstein, M. Wang. Validation of a clinical prediction rule for pediatric abusive head trauma. Pediatrics, 134 (2014), pp. e1537-e1544

73. R.P. Berger, J.B. Fromkin, H. Stutz, K. Makoroff, P.V. Scribano, K. Feldman, L.C. Tu, A. Fabio. Abusive head trauma during a time of increased unemployment: a multicenter analysis. Pediatrics, 128 (2011), pp. 637-643

74. M.C. Pierce, J.N. Magana, K. Kaczor, D.L. Lorenz, G. Meyers, B.L. Bennett, J.T. Kanegaye. The prevalence of bruising among infants in pediatric emergency departments. Ann. Emerg. Med., 67 (2016), pp. 1-8