Chapter 12: Identifying blast trauma in the human skeleton: applications for forensic anthropology

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Summary

Trauma analysis is an integral part of the forensic anthropologist's role in the study of skeletonized human remains. An increasingly common type of injury, however, remains vastly unexplored in the anthropological literature: blast injury. This chapter aims to provide more information on how blast injury can present in the human skeleton, offering the beginning of a guide for anthropologists looking to identify this type of trauma. The study was done by reviewing publications that detail trauma observed in victims of explosive incidents and extracting data on skeletal trauma from a forensic anthropology perspective by calculating the prevalence of these injuries. Overall, the effects of blast were noted to affect nearly every part of the skeleton when the data was reviewed in combination.

Keywords: blast trauma, forensic anthropology, explosion, conflict, human skeleton

1. INTRODUCTION

When human remains are in an advanced state of decomposition, skeletonised, fragmented and/or burnt, forensic anthropologists working in a medico-legal or humanitarian context can play a valuable role in assisting with the identification of the deceased and understanding the circumstances surrounding death (e.g. see Baraybar and Gasior 2006; Kimmerle and Doying 2007; Tersigni-Tarrant and Shirley 2012; Christensen *et al*. 2013; Komar and Buikstra 2008). In particular, forensic anthropologists working on past conflicts may encounter remains that have incurred traumatic injury, including blast trauma (Willits *et al*. 2015). Amongst the questions the forensic anthropologist must consider during the analysis of skeletal trauma (e.g. see Passalacqua and Rainwater, 2015) they should also deliberate whether the damage on the skeleton is ante-mortem, peri-mortem or post-mortem; and if ante-mortem or peri-mortem, whether the injuries have been caused by blunt, sharp or ballistic force (although these terms can change). Blast trauma in forensic anthropology has not been explored much (Christensen and Smith 2015, Szleszkowski, *et al*. 2020), neither does it tend to be taught. This paper addresses skeletal injury resulting from human exposure to the detonation of an explosive device. Such exposure can occur in military and civilian environments as a result of war, terrorism, industrial and domestic accidents amongst others. Recently, blast injury appears to be occurring more frequently in civilian environments due to terrorist attacks (Maniscalco and Christen, 2010; Nelson, *et al*. 2006; Owens, *et al*. 2008); whilst in modern warfare, the lethality associated with explosive munitions has exceeded that associated with gunshot wounds (Belmont *et al*. 2010) and are the mechanisms responsible for most deaths (Kang *et al*. 2012, Zachar *et al*. 2013; Breeze *et al*. 2011; Schoenfeld *et al*. 2013).

While the soft tissue characteristics of explosive injuries are well-documented in the literature, skeletal injuries have not been studied as extensively (Christensen and Smith 2015). However, there is much that can be learnt from clinical research and publications (e.g. Rozenfield *et al*., 2019; Edwards *et al*. 2016; Gregory *et al*. 2016), and a better understanding of how blast injury can affect the human skeleton is crucial to the forensic anthropologist's ability to hypothesize a mechanism responsible for a particular skeletal trauma. Of course, these interpretations of injury patterns would be part of a collaborative effort alongside forensic pathologists, experts in explosives and explosion investigation, and a number of other professionals and specialists (e.g. see Edwards *et al*. 2016). This is particularly helpful for understanding the position of the device in relation to the victim, the circumstances surrounding death, for providing evidence of crimes against humanity (Connor 2009), and generally informing any subsequent investigations, including the reconstruction of battle events and potentially helping with identification of the deceased in earlier 20th century conflicts. In terrorist incidents, differentiating trauma caused by the blast itself from secondary effects can provide intelligence about the device used (Delannoy, *et al*. 2020), how it affected surrounding structures, and the consequences for human injury. Today, understanding how the deaths occurred or the damage caused is important for a variety of purposes, from improving medical applications in theatre, assessing morbidity and mortality, to designing better combat armour or even to being able to provide the most accurate information possible for the family of a fallen soldier (Bieler *et al*. 2020; Breeze *et al*. 2014; Bull *et al*. 2016; Callaway and Burstein, 2020).

Investigations that have differentiated blast injury from other types of trauma in skeletonised remains have done so by consulting descriptions in clinical literature (Loe *et al*. 2014; Willits *et al*. 2015), but they did not use any anthropological guidelines as no such standardisation exists.

The overall objective of this paper is to increase understanding and awareness of how blast injury affects the skeleton to provide guidelines for forensic anthropologists looking to identify such injuries. It aims to:

1) Identify how blast trauma affects the skeleton to assist forensic anthropologists in searching for this evidence when examining human remains;
2) Assist with the differential diagnosis of blast trauma and interpretation of skeletal injuries caused by blast
3) Consider blast in contexts where human remains are commingled and incomplete, for example the presence of certain body parts in mass graves;
4) Understand how blast trauma may be evidenced in the skeleton and distinguishing this from other types of trauma;
5) Assist with the identification of mechanism of death.

1.1. Explosions and Explosives

An explosion can be described as the rapid release of a large amount of energy that results in a violent evolution of gases and heat (Brown *et al*. 2013), and are categorised as mechanical, chemical and nuclear (Akhavan 2011). The majority of cases where there have been explosive events resulting from the use of explosive devices, whether they be improvised or conventional ordnance, will be chemical explosions.

Chemical explosives may be classed as either high-order or low-order depending on the speed in which they release energy. A low-order explosive, while still able to release large amounts of energy, does so in a slower process called “deflagration,” which is likened more to burning the material at subsonic speeds (Sattin *et al*. 2008). In contrast, a high-order explosive ´detonates´ with supersonic speed (0.001 second) as the reactive material rapidly transforms into pressurized gas and heat (Sattin *et al* 2008). However, if sufficiently confined, low explosives can also transition to detonation. Upon detonation, these rapidly expanding gases will develop spherically from the epicentre of that reaction, creating what is referred to as a “blast wave” (Beveridge 2012). The high velocity and high pressure of the blast wave compresses the surrounding atmospheric air, producing a peak incident pressure before dropping to a negative pressure and then finally levelling off at the atmospheric level (Beveridge 2012; Institute of Medicine 2014). The peak overpressure of a blast wave varies between incidents but is considered potentially lethal once it exceeds 60-90 PSI (pounds of force for square inch of area). After these expanding gases create the blast wave and peak incident pressure, the negative phase of the wave forms a strong vacuum, creating what is known as a “blast wind” (Beveridge 2012). This high velocity wind can move upward of 2,400 km/h and exert an overpressure of greater than 100 PSI at its most lethal levels (Institute of Medicine 2014). The blast wave will propel fragmentation during an explosive event, as well as causing a variety of damage to surrounding structures (Boffard and McFarlane 1993).

The behaviour of a blast varies between incidents due to the effects of the type and quantity of explosive used, the orientation of the explosive device, the environment in which detonation occurs, and even the geometry and medium of the surroundings which can have a significant effect in reflecting blast waves (Rose and Smith 2002; Remennikov and Rose 2005; Smith and Rose 2006; Cullis 2001; Kosashvili *et al*. 2009; Wolf *et al*. 2008).

2. Overview of Blast Injury

2.1. History of research

Widespread manufacturing and use of high explosives did not commonly appear until the First World War (Brown 1998). The type of munitions used at this time was largely shaped by the prevalence of trench warfare, with notable weapons including hand grenades and small mortar-launched explosives (Tucker 2014). With these came a number of medical studies focusing on both internal and external blast injuries (Hooker 1924; Mott 1916; Rusca 1915). During the Second World War, with the addition of aerial bombs and marine torpedoes, further studies were undertaken and continued well into the 1960s (Zuckerman 1940; Krohn *et al*. 1942; Cameron *et al*. 1943; Benzinger 1950; Chiffelle 1966; Richmond, *et al*. 1968, see also Wightman and Gladish 2001); with a particular emphasis on pulmonary injury ("blast lung") (Dean *et al*. 1940; BMJ 1941; Ross 1941). Many studies at the time were also based on animal experimentation (Roberts *et al*. 1953; Celander *et al*. 1955; Richmond *et al*. 1961; Chiffelle 1966). A number of other physiological studies, based on nuclear weapons, also emerged after the Second World War (LeRoy 1947; Folley 1952; Oughterson 1956; Preston 2003). This research expanded with the Korean and Vietnam wars, and in particular with the advancements in mortar technology, hand grenades, land mines and napalm as a chemical (Boose 2013; Kumar 2010; Tucker 2011). The literature examining blast trauma and injuries at this time were aimed at discussing treatment and survivability (Belmont *et al*. 2010; Reister 1973; Ziperman 1954), with a particular focus on brain trauma as a result of blast, repair of vascular damage, and treatment of traumatic amputations (Levitsky *et al*. 1968; Rich, Baugh and Hughes 1970; Hammon 1971).

Clinical literature has differentiated blast injury into four basic categories: primary, secondary, tertiary, and quaternary. It should be noted that a fifth category, quinary, has also been used by a number of experts (Champion *et al*. 2009, Wolf *et al*. 2009). The primary category refers to injuries that result from the blast wave itself and mainly affects gas-filled organs (bowel, lungs, and tympanic membrane) due to the stress caused by dynamic pressure changes (DePalma *et al*. 2005). Victims of primary blast injury are usually in close proximity to the explosion (Institute of Medicine 2014). This is true in both military and civilian settings, even though victims in the former are usually equipped with body armour (Stuhmiller *et al*. 1991). It has also been observed that there are significantly more ($p=0.024$) tympanic membrane injuries in closed space incidents than there are in open spaced incidents (Edwards *et al* 2016).

Secondary and tertiary injury results from the actions of the blast wave. Secondary injuries are caused by the debris and fragmentation displaced and carried by the blast wave acting as projectiles (DePalma *et al*. 2005) and results in the majority of deaths (Christensen *et al*. 2012) and injuries (e.g. see Yazgan and Aksu, 2016). Fragmentation caused by the actual explosive device components is referred to as 'primary' fragmentation, whilst that resulting from additional fragmentation added to the device or other local material is 'secondary' fragmentation (Champion *et al*. 2009; Mathews and Koyfman, 2015. This typically results in penetrating and blunt injuries. In contrast, tertiary injuries are caused by an individual being displaced by the blast wind and impacting on an immovable object (Singh *et al*. 2016). These events typically result in fractures and traumatic amputations. Both secondary and tertiary mechanisms have been associated with high incidents of brain trauma (Taber, *et al*. 2006). Quaternary trauma comprises miscellaneous injuries—essentially anything that cannot be described in association with the first three mechanisms. These injuries include carbon monoxide poisoning, dust and smoke inhalation, burns from secondary fires, and crushing injuries from building collapse (Wightman and Gladish 2001). Complications of previous injuries are also included under quaternary injury in some literature. In addition to these four commonly discussed mechanisms, a quinary category of injury was suggested by Kluger and colleagues (2007). This relates to the development of a hyperinflammatory state and hemodynamic instability thought to relate to toxic by-products produced by an explosion (Kluger *et al*. 2007); although regarding forensic anthropology, Sanabria and Rodriguez (2016) indicate that although this is not really affecting bone, there are exceptions where bone is incrusted from one individual to another (ie contamination) and this may be considered quinary.

More recently, with military action in Iraq and Afghanistan, a number of clinical publications and research has been undertaken, although focused mainly on mortality, survivability, long-term outcomes, and the development of better medical treatments as opposed to blast injury classification and description (Dougherty 1999; Harrisson *et al*. 2007; Kelly *et al*. 2008; Penn-Barwell *et al*. 2015; Russell *et al*. 2014; Walker *et al*. 2014). An increase in the use of explosive devices in terrorist attacks, whether delivered through letter bombs, pre-placed devices, suicide bombings, cars, etc. has deemed this type of trauma relevant within the civilian sector as well (Wightman and Gladish 2001, INTERPOL 2015, Morley and Leslie 2007). Experimental research for the military has also seen an increase in recent years to improve protection (e.g. Nguyen *et al*. 2019), as is the value of imaging in blast trauma analysis (e.g. see Singh *et al*. 2016). Finally, it should be noted that blast injury can be entirely unrelated to conflict. The potential risk for an accidental explosion is present in industrial settings like mines, refineries, chemical stores, and oil processing plants such as the accidental explosion of 1917 the Halifax Disaster (Scanlon 1998); Armstrong 2002). Some of this work derives from investigating industrial disasters (e.g. Zio and Aven 2013; Groves 2006; Eckhoff 2003).

2.2. Blast injury and forensic anthropology

Potential cause of traumatic lesions in the skeleton are usually presented as a trinity in anthropological literature: blunt-force trauma, sharp-force trauma, and ballistic or projectile trauma (Kimmerle and Baraybar 2008; Passalacqua and Fenton 2012; Christensen *et al*. 2013; İşcan and Steyn 2013; see also Davidson *et al*. 2011).

Whilst the clinical literature extensively discusses soft tissue injury (Mayorga 1997; Wightman and Gladish 2001; Morley and Leslie 2007; Ritenour and Baskin 2008), skeletal injuries are rarely the focus and are usually not mentioned until tertiary injury. Recent literature by forensic anthropologists, however, has recorded skeletal injuries resulting from primary and secondary mechanisms as well (Kimmerle 2008; Christensen *et al*. 2012; Christensen & Smith 2013; Dussault *et al*. 2014; Christensen and Smith 2015; Dussault *et al*. 2016; Dussault *et al*. 2017), with some using a biomechanical approach to understand specific patterns of injury (Ramasamay *et al*. 2011).

Forensic anthropologists, Kimmerle and Baraybar (2008) began discussing the differences between gunshot and blast wound patterns in the skeleton, based on their examination of fragmentation wounds and fractures in gunfire, mortar and grenade victims from the Kraviča, Bosnia and Herzegovina warehouse massacre. The latter authors also included a number of case studies in their volume (Seneviratre, 2008; Pachón, 2008; Samarasekera, 2008). Christensen and colleagues (2012; Christensen and Smith 2013) took an experimental approach, studying the primary and secondary mechanisms of blast injury in porcine proxies of the human skeleton (two in boats, three on suspended rigs), finding a unique rib butterfly fracture pattern (Christensen and Smith 2013).

Dussault *et al.* (2014) investigated past military and terrorist incidents involving explosives and the effect on the skeleton, presenting prevalence patterns for injuries rather than specific characteristics of use in anthropology, emphasizing the need for further work. Subsequent work (Dussault *et al*. 2016; Dussault *et al*. 2017) employed statistical analysis to quantify patterns and differentiate types of contexts such as combat-related injuries versus war crimes, rather than individual trauma identification.

More recently, a number of skeletal trauma books in forensic anthropology have included chapters and case studies on blast trauma. These include further research by Christensen and Smith (2015) and a number of cases from past conflicts, such as the Korean War (Willits *et al*. 2015). In recent years, blast injury has been identified in a number of WWI and WWII casualties and some of these reports have been published (Loe *et al*. 2014; Barker *et al*. 2014; Dussault *et al*. 2017, Dewilde *et al*. 2018). Certainly, one of the most comprehensive papers is a chapter by Sanabria and Rodríguez (2016). Nevertheless, co-authored journal papers seem to include forensic anthropologists such as in the analysis of remains from terrorist attacks in France, co-authored by forensic anthropologist Tania Delabarde (Delannoy *et al*. 2019) or case studies from Israel, co-authored by forensic anthropologist Tzipi Kahana, although mainly focusing on identification in bombing victims (e.g. Kahana *et al*. 1997; Hiss and Kahana, 1998)

3. Materials and methods

This paper utilises clinical literature on blast trauma as well as anthropological publications, compiled and updated from the second author´s dissertation (Webster 2014). It also draws on the practical forensic experience of some of the authors.

3.1. Literature based data

In order to reconstruct how the skeleton may be affected by blast trauma, information was extrapolated primarily from the clinical literature on the soft tissue, noting the affected anatomical regions and the presence of any fractures, amputations, and even soft tissue injuries such as subdural hematoma. Injury prevalence was calculated if this had not been provided, and comparisons between incidents and military and civilian context trauma were included. The trauma type, pattern and prevalence were also analysed bearing in mind environment (open, semi-open closed space etc; see Rozenfeld *et al*. 2016), type and amount of explosive, subsequent building collapse, among the extensive different variables that can alter presentation of trauma (see a review in Sanabria Medina and Rodríguez 2015). Incident specific journal publications were separated according to terrorism and military-related incidents rather than type of explosion or particular settings. Data on non-conflict-related incidents involving human injury by explosives (e.g. mining accidents) were excluded as information focused on mortality rather than description of injuries, or blast injury was not differentiated from other types within the trauma data.

For each incident, the following information was collected: name of incident, characteristics, device information, relevant trauma, and source(s) of data. Data was compiled from thirteen pre-2005 civilian incidents (Table 12.1) using the Global Terrorism Database (https://www.start.umd.edu/gtd/), with information from post-1970 events including the type of device used (NCSTRT 2015). In addition to those civilian incidents, four conflicts were selected (WWI, WWII, Korean War, Iraq War).

Table 12.1: Contexts included in this study, the year they occurred, and the sources providing the injury data.

Incident	Year			Source(s)
7/7 London Bombings	2005	Suicide bombings on 3 underground trains and 1 bus	56 killed including the 4 bombers c. 700 injured	(Aylwin, *et al*. 2006)

Madrid Train Bombings	2004	10 explosive devices on commuter train system	191 killed and c. 2000 injured	(Turegano-Fuentes *et al*. 2008)
Israel Bus Bombings	Pre-1989	6 kg of TNT in the middle of a bus, under seat	3 dead and c 29 injured	(Katz *et al*. 1989)
Bologna, Italy Bombings	1980	TNT-based time-bomb left in an unattended suitcase detonated at the central train station in Bologna	85 killed and c 200 injured	(Brismar and Bergenwald 1982)
Oklahoma City Bombings	1995	car bomb detonated outside building	168 killed and c 680 injured	(Mallonee, *et al*. 1996; Quintana, *et al*. 1997; Hogan, *et al*. 1999)
Beirut Airport Bombings	1983	truck loaded with the equivalent of 12 tons of TNT crashed into a terminal and detonated	234 killed and c.112 injured	(Scott, *et al*. 1986; Frykberg, *et al*. 1989)
Paris Bombings	1985-86	11 terrorist bombings in a variety of locations	13 killed and 255 injured	(Rignault and Deligny 1989)
Istanbul Turkey Bombings	1976-2000	Various locations throughout the years	120 killed but injured not estimated	(Yavuz, *et al*. 2004)
Northern Ireland Bombings	1969-1992	Against military and civilian, intended to make a statement	9 killed and 1532 people admitted into emergency services	(Hadden, *et al*. 1978; Hull, *et al*. 1994)
Argentine Israelite Mutual Association Bombing	1994	a car bomb outside building. 300kg ammonal-based device	86 killed and over 200 injured	(Biancolini, 1999)
Birmingham Pub Bombings	1974	Two explosions in two pubs	21 killed and 182 injured	(Waterworth and Carr 1975a; Waterworth and Carr 1975b)
USS Cole Terrorist Bombing[1]	2000	Suicide bomber 200-300kg explosives	19 killed includeing 2 attackers and 39 injured	(Langworthy *et al*. 2004)
Nairobi US Embassy Bombing	1998	TNT-based truck bomb	211 killed and over 4000 injured	(Kalebi and Olumbe 2006)
World War I (Veneto, Italy battle)	1915-1918	The battle of Vitorio Vennetto	Excavated mass grave with 7 Italian soldiers	(Gaudio, *et al*. 2013)
World War I (Battle of Fromelles)	1916	Battle of Fromelles, France	C 250 Australian casualties found in mass graves	(Loe, *et al*. 2014)
World War II (Malta Bombings)	1939-1945	Italian and German forces fighting against British forces in 1941-1942	8 patients (3 fatalities and 5 injured)	(Turnbridge and Wilson 1943)
Korean War	1950-1953	Explosive projectiles, grenades, mines, etc.	Data from two case studies of unidentified soldiers from the Korean War (Willits *et al*. 2015) and various figures (Reister, 1973)	(Willits *et al*. 2015; Reister 1973)
Iraq War	2004	18 close-proximity blast injury US patients	9 non-survivors	(Nelson *et al*. 2006, 2008)

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[1] Please note that while the attack on the USS Cole did occur on a military vessel, it is considered a terrorist attack. It occurred while the crew was in port and refuelling, not in a combat environment and is therefore included in this part of the study.

Events were selected for inclusion when the literature contained detailed information on skeletal injuries, as well as how many victims sustained these injuries. Articles containing only soft tissue information or descriptive data without any indication of distribution across the population were omitted. Data was tabulated for each incident and prevalence for all anthropologically-relevant injuries (fractures) was calculated, dividing number of people with the injury of interest (from a particular incident) by the number of people reported as being injured in that incident. After tabulation of the injuries, categories of injury that could be applied to all incidents were created to allow for comprehensive analysis. These were fractures divided according to the following anatomical regions or skeletal elements: skull (neurocranium), face (including orbital fractures), sternum, ribs, spine (vertebrae), scapula, clavicle, pelvis, upper limb, lower limb, non-specific limb fracture, metacarpal (hand), metatarsal (foot), upper limb amputation, lower limb amputation, non-specific amputation.

3.1.1. Injury Reporting and Population Mortality

Injury reporting was suspected to differ between studies reporting only on surviving victims and studies reporting only on deceased victims. To investigate this, the occurrence of skull fractures was compared between these two types of studies. Three incidents had data on both survivors and fatalities, allowing for direct comparison to gain better insight into this trend. These incidents were: the Birmingham Pub Bombings; USS Cole Bombing; and the Beirut Airport Bombings. Odds ratios (including confidence interval) were calculated to ascertain support for the hypothesis of association with increased risk of fatality. Due to the lack of resources publicly available on skeletal trauma caused by explosive devices during military action (e.g. WWII, Korean War, Iraq War), it was decided that the military data here would be presented in a descriptive manner only. Moreover, often when detailed information on fractures was provided, the injury causes (vehicle accident, ballistic injury, blunt injury, blast injury, etc.) were combined, preventing any analysis of what was caused specifically by a blast. This was frequently seen in the US Surgeon General's reports (Willit, *et al*. 2015). In the civilian environment, the level of detail available is usually higher as there is an effort by the medical community to improve care and create guidelines for future incidents (Covey 2002; Kluger *et al*. 2004).

3.2. Limitations

There were a number of limitations regarding data access, including the use of secondary sources, such as potential bias in data acquisition and interpretation. One of the main issues is that many of the studies are clinical cases where there is no focus on skeletal trauma. Indeed, the use of secondary sources as opposed to primary data such as hospital records, radiographs and any other documentation has been a limiting factor; especially bearing in mind that skeletal lesions or injury are not the primary focus in data reporting. Moreover, data on military incidents has been limited. Added to this, is a potential issue of bias as to what is published. The data has come from hospital records of admitted patients, rather than including that of those treated by emergency services or emergency departments. In fact, some of the sources provide information on the survivors, others on both the living and the dead, and others mainly on the deceased.

Another challenge was the level of detail employed in the reporting of injuries, which varied between sources. On the one hand, sources where the trauma listed indicates "fracture and/or dislocation of the back, chest, or pelvis" (Mallonee *et al*. 1996); on the other hand, other publications provided much greater detail, for example describing a "compound fracture of the medial malleolus" (Waterworth and Carr 1975b) or "medial epicondyle humeral fracture" (Delannoy *et al*. 2019). Some of this data may be limited for fatalities too as there may not have been a complete autopsy. For example, in the 7/7 London Bombings the decision was made that invasive post-mortem examinations would not be performed in the temporary mortuary (HM Coroner 2011). Though radiography and fluoroscopy were performed, this was not focused on trauma analysis (Silver 2015).

4. Results

Table 12.2 summarises the anthropologically-relevant data extracted from each incident, as well as the prevalence values calculated. As stated earlier, this data will be based on survivor data, others on fatalities or a combination of both. For more detailed information please refer to Webster (2014).

Table 12.2: Data collection from terrorism and military-related incidents.

Incident	Characteristics of Incident, type of device and delivery method	Trauma Relevant to Forensic Anthropology	Source(s)
London Bombings, UK **July 2005**	Terrorist attack against civilians by suicide bombers. 4 urban scenes: explosions in 3 underground trains (ultra-closed environment, 1 station narrower and deeper than the rest with greater number of fatalities) and on 1 bus (closed environment). The suicide bombs (Command –human-initiated devices) were homemade peroxide-based devices carried in backpacks (<10 lbs per device)	Skull vault fracture (7.4%) Base of skull fracture (3.7%) Facial fractures (22.2%) Rib fractures (7.4%) Unspecified spinal injury (7.4%) Upper limb amputation (3.7%) Lower limb amputation (7.4%) Long bone fractures (14.8%) Metacarpal fractures (11.1% Metatarsal fracture (3.7%) Extra-axial hematoma (18.5%)	(Aylwin, et al. 2006) Data from Royal London Hospital and ONLY the "seriously injured" patients (n=27) were considered
Israel Bus Bombings	Civilian bus terrorist attack, urban explosion caused by c.6 kg TNT detonated under a bus seat	Head trauma (13.8%) Rib fractures (10.3%) Amputation (3.4%) Limb fractures (24.1) Comminuted fractures (10.3%)	(Katz, et al. 1989) Hospital data on admitted surviving patients (n=29)
Madrid Train Bombings, Spain **March 2014**	Civilian terrorist attack, urban explosion on train (closed environment). These were remote-triggered devices (cellular phone activated) with a cumulative amount	Base of skull fracture (1.8%) Maxillofacial fractures (9.4%)	(Turegano-Fuentes *et al*. 2008a, 2008b). Hospital and EMS data (n= 512 patients)

Incident	Characteristics of Incident, type of device and delivery method	Trauma Relevant to Forensic Anthropology	Source(s)
	of explosives of 22lbs distributed in several backpacks	Vertebral fracture (4.5%): C1 (0.19%), C7 (1.0%), T1-T6 (3.0%), Lumbar (0.8%) Sternal fractures (0.19%) Fractures not including head, chest, and spine (15.8%) Rib fractures (8.4%) Clavicle facture (1.0%) Scapula fracture (0.39%) Humeral fractures (1.9%) Ulna-radius (1.0%) Metacarpal fracture (1.37%) Pelvis fracture (0.19%) Femur fractures (1.76%) Tibia-fibula fractures (3.9%) Traumatic amputations (3.7%) Ankle fractures (1.37%) Metatarsal fractures (0.39%) Subdural hematoma (1.6%)	
Bomb in Bologna, Italy, 1980	Civilian terrorist attack, urban explosion at Bologna central railway station (closed environment). Plastic explosive, TNT	Skull fracture (9.3%) Orbital fracture (1.9%) Brain contusion (5.6%) Spine (6.5%) Arm fractures (18.7%) [scapula=4, humerus=6, radius/ulna=8, hand=6] Traumatic forearm amputation (0.9%) Legs (16.8%) [Femur=4, tibia/fibula=8, ankle=5, foot=7] Finger/toe amputation (1.9%)	(Brismar and Bergenwald 1982) Patients admitted to hospital, survivor and deceased (n=107)
Oklahoma City Bombing, USA, 1995	Civilian terrorist attack. Urban explosion in front of Alfred P. Murrah Federal Building. Open environment with subsequent building collapse. 4,000 lbs of ammonium nitrate delivered by vehicle, detonated in front of building	Face and neck fracture/dislocation (37.0%) Back, chest, or pelvis fracture/dislocation (25.0%) Leg fracture/dislocation (40.0%) Arm fracture/dislocation (38.0%) Multiple fractures (37.0%)	(Mallonee, et al. 1996) Hospital data from 759 injured, from Medical examiner records (deceased n=13),further hospital records (injured n=223), physician surveys (minor injuries n=972), building

Incident	Characteristics of Incident, type of device and delivery method	Trauma Relevant to Forensic Anthropology	Source(s)
			occupant and survivor survey (n=595)
		Fractures (8.3%)	(Hogan, et al. 1999) Data from all 13 emergency departments (n=388)
		Skull fracture (89.5%) Amputations (31.0%)	(Quintana, et al. 1997) Paediatric fatalities (n=19)
Beirut Airport Bombing, Lebanon,1983	Terrorist attack at US Marine Corps facility in Beirut. Truck containing equivalent of ~12,000 pounds of TNT drove into facility and exploded (closed environment)	Facial fractures (7.0%) Vertebral fractures (2.3%) Scapular fractures (3.5%) Upper extremity fractures (11.8%) Hand fractures (3.5%) Pelvis fractures (4.7%) Femoral fractures (7.1%) Tibia-Fibula fractures (10.6%)	(Frykberg *et al*. 1989). Survivor data (n=85)
		Skull Fracture (28.3%): Survivors (11.6%), Fatalities (36.3%) Facial Fracture (8.7%): Survivors (5.4%), Fatalities (10.6%)	(Scott, et al. 1986) Deceased and living data (n=346)
Paris Terrorist Bombing, **France, 1986**	Civilian terrorist attack, 11 urban incidents in Paris, 2 open air environment, 9 closed environment inside buildings. Homemade devices containing TNT or TNT equivalent	Head/neck (total: 5.4%; closed: 3.9%; open: 1.5%) Trunk (total/closed: 1.0%) Arm (total: 2.9%; closed: 2.4%; open: 0.5%) Forearm (total: 1.0%; closed: 0.5%; open: 0.5%) Hand (total: 4.9%; closed: 3.9%; open: 1.0%) Thigh (total/closed: 0.5%) Leg (total: 6.8%; closed: 0.5%; open: 6.3%) Foot (total: 3.9%; closed: 3.4%; open: 0.5%)	(Rignault and Deligny 1989) Data from the 11 terrorist bomb explosions, hospitalized victims, survivors and fatalities (n=205)
Bombings in Istanbul, Turkey, 1976-2000	Terrorist bombings from variety of locations; mixed of closed and open environments.	Skull fractures (37.5%) Facial bone fractures (14.2%) Rib fractures (30.0%) Sternum fractures (4.2%)	(Yavuz, et al. 2004) Data from mortuary (deceased), includes victims and attackers (n=120)

Incident	Characteristics of Incident, type of device and delivery method	Trauma Relevant to Forensic Anthropology	Source(s)
		Thoracic vertebrae dislocations and/or fractures (6.7%) Abdominal vertebrae dislocations and/or fractures (5.0%) Scapula fractures (1.7%) Upper limb amputation (11.7%) Pelvic fractures (5.8%) Lower limb amputation (4.3%) Limb bone fractures (42.5%) Upper and lower limb amputation (10.0%)	
Northern Ireland Bombings	Civilian terrorist bombings, urban variety of settings (open, closed, unspecified). Multiple bomb types (command, time, victim operated), including vehicle bombs, open charges and culvert bombs	Skull fracture (0.7%) Nasal fractures (0.3%) Other facial fractures (0.4%) Ribs (simple: 0.13%; compound: (0.19%) Vertebrae (simple (0.065%) Pectoral girdle (compound: 0.13%) Humerus (simple: 0.065%; compound: 0.13%) Radius/ulna (simple: 0.59%; compound: 0.13%) Hand (simple: 0.13%; compound: 0.52%) Femur (simple: 0.13%; compound: 0.46%) Tibia/fibula (simple: 0.13%; compound: 0.65%) Ankle (simple: 0.39%; compound: 0.33%) Foot: (simple: 0.26%; compound: 0.39%)	(Hadden *et al*. 1978) A&E records of surviving patients from 1969-72 (n=1532)
		Amputation (34.0%) Comminuted fractures on amputations (17.6%) Spiral fracture (8.8%) Open joint (5.6%) Segmental fracture (3.0%)	(Hull, et al. 1994) Deaths (n=100) between 1987-1992 Study focuses on amputations and fractures at amputation site
Argentine Israeli Mutual Association (AMIA) Building	Civilian terrorist bombing, urban bombing of the 7 story AMIA building via car bomb containing 660 lb (300 kg) of ammona and placed at entrance	Skull fractures (16.7%) Facial fractures (5.5%) Amputations (11.1%)	(Biancolini *et al*. 1999) Patients from Clínicas University Hospital, survivors and fatalities (n=18)

Incident	Characteristics of Incident, type of device and delivery method	Trauma Relevant to Forensic Anthropology	Source(s)
Bombing, 1994		Compound open fractures (16.7%) Multiple open fractures (5.5%) Comminuted fractures of tibia- and fibula (5.5%)	
Birmingham Pub Bombings, UK,1974	Civilian terrorist attack, urban bombing of two pubs, one at basement level. Homemade device with shards of metal.	Skull fractures (47.6%) Orbit fractures (14.3%) Jaw fractures (19.0%) Amputations (43.0%) Open femur fracture (14.3%) Open tibia/fibula fracture (19.0%) Other fractures (33.3%)	(Waterworth and Carr 1975a) Deceased patients at the Birmingham General Hospital (n=21)
		Skull fractures (1.6%) Open tibia fractures (4.9%) Compound medial malleolus fracture (1.6%) Open fibula fractures (3.3%)	(Waterworth and Carr 1975b) Surviving patients from Birmingham General Hospital (n=61)
USS Cole Terrorist Bombing, Yemen, 2000	Terrorist bombing of the USS Cole while refuelling in Aden Harbour. Explosions amid ships and adjacent to port side (closed environment). Ship badly damaged, but no structural collapse Dynamite. Fiberglass boat with C4 explosives and 2 suicide bombers.	Long bone fractures (92.9%) Pelvic fracture (50.0%) Spine fracture (71.4%) Skull fracture (85.7%) Rib fractures (100.0%)	(Langworthy, Sabra and Gould 2004) Fatality data (n=14)
		Open long bone fractures (10.3%) Spine fractures (2.7%) Skull fractures (2.7%) Rib fractures (7.7%) Clavicle fractures (2.7%)	(Langworthy, Sabra and Gould 2004) Survivor data (n=39)
Nairobi US Embassy Bombing, Kenya, 1998	Terrorist attack. Blast resulted in massive building collapse, adjacent buildings badly damaged. Occurred simultaneously with another attack in Tanzania TNT-based truck bomb	Skull fractures (28.4%) Rib fractures (22.9%) Extremity fractures (18.9%)	(Kalebi and Olumbe 2006) Fatality data (n=201)
World War I: Veneto	Primary WWI mass grave excavated from mountain area in the Veneto	Comminuted fractures to Vertebrae, Ribs, Clavicle, Scapula, Humerus, Femur, Os Coxae, Tibia and Fibula	(Gaudio, et al. 2013) Data from 7 individuals. Descriptive data only

Incident	Characteristics of Incident, type of device and delivery method	Trauma Relevant to Forensic Anthropology	Source(s)
Region of Italy	region. Grenades and fragmentation grenades	Traumatic amputation of lower limbs	from those suspected of being affected by blast
World War I: Battle of Fromelles, France, 1916	Breastwork and trench warfare over two days in northern France between Australian and British vs German troops. Explosive munitions including artillery, grenades, mortars, and bombs	Head fractures (79.5%) Neck fractures (61.5%) Thorax fractures (85.9%) Left upper limb fractures (16.7%) Right upper limb fractures (15.4%) Left lower limb fractures (14.1%) Right lower limb fractures (15.4%)	(Loe *et al*. 2014) 250 sets of human remains recovered from 6 graves; n=78 affected by blast injury
Malta Bombings in WWII	World War II, period of heavy bombing in Malta (Dec 1941-Apr 1942) primarily through air raids	Rib fractures (12.5%)	(Turnbridge and Wilson 1942) Case studies (n=8 patients). Survivors and fatalities (rib fractures seen in survivor)
Korean War, 1950-1953	Circumstances surrounding each event mostly unknown, except for witness account that Case 2 (Willits *et al*. 2015) had been kneeling in a foxhole when hit with mortar fire. Explosive projectile shells, grenades, and land mines	Skull fracture, Scapula fracture**,** Rib fractures, tarsal fractures and embedded metal fragments in foot. Cluster of projectile injuries consistent with lower extremities and feet Comminuted fracture of tibia, Right fibula and Tarsal fractures	(Willits *et al*. 2015) Data from two case studies of unidentified soldiers from the Korean War
		Fractures (12.2%) Amputations (64.8%)	(Reister 1973)
IED Explosions in Iraq between Aug-Sept 2004	Improvised explosive device (IED) explosions affecting military personnel wearing Kevlar helmets, ballistic eye protection, and full-body armour including small arms protective insert plates, neck protectors, and groin protectors	Skull fractures (33.3% total, 55.5% of fatalities, 12.5% survivors) Mandible fracture (5.5%) Lumbar vertebrae fracture (11.1%) Sacrum fracture (5.5%) Humerus fracture (16.7%) Femur fracture (16.7%) Tibia fracture (11.1%) Fibula fracture (5.5%) Ankle/foot fracture (5.5%) Metatarsal fracture (5.5%) Near amputation, upper limb (5.5%) Near amputation, lower limb (5.5%)	(Nelson *et al*. 2008) Case studies (n=18) of military personnel, including 5 that were specifically in vehicles or Humvees

4.1.2. Combined Data- anatomical regions and skeletal elements

Amongst the civilian terrorist data sets, 12 incidents[2] (12/13) reported the presence of skull fractures amongst the injured (Figure 12.1). At 89.5%, the paediatric population from the Oklahoma City Bombing has the highest percentage of skull fractures, followed by the USS Cole Bombing deceased victims with 85.7%. The lowest percentages of skull fractures were seen in the Northern Ireland bombings (0.7%) and the surviving victims of the Birmingham Pub Bombings (1.6%). Eight incidents (8/13) reported facial fractures[3] with the highest number reported in the 7/7 London Bombings (22.2%), followed by the Birmingham Pub Bombing fatalities (14.3%). The lowest prevalence of facial fractures were observed in the Northern Ireland (0.7%) and Bologna (1.9%) bombings.

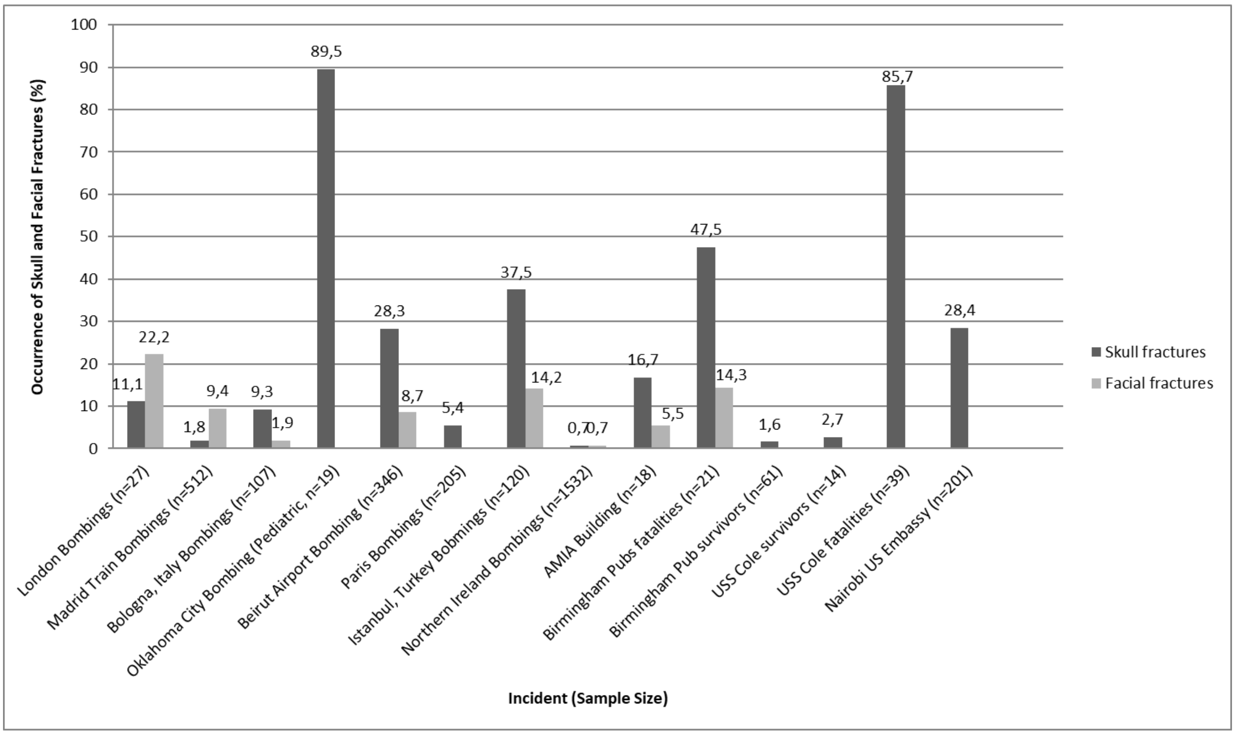

Figure 12.1: Skull and facial fracture percentages across all terrorism incidents.

Seven incidents[4] (7/13) reported rib fractures. The highest— with 100.0% of victims sustaining rib fractures—was the fatality population in the USS Cole terrorist bombing, followed by 30.0% in the Istanbul data (Figure 12.2). The lowest incidence of rib fractures was observed in the Northern Ireland bombings at 0.32% and the London Bombings at 7.4%.

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[2] These 12 incidents are represented on the graph by 14 data sets due to repeats when a population study is split by mortality.

[3] Here, this included orbital fractures which were seen in the Bologna, Italy bombings and Birmingham Pub Bombings, as well as nasal fractures, which were reported in the Northern Ireland bombings.

[4] These 7 incidents are represented by 8 data sets due to repeats when a study is split by mortality of the population.

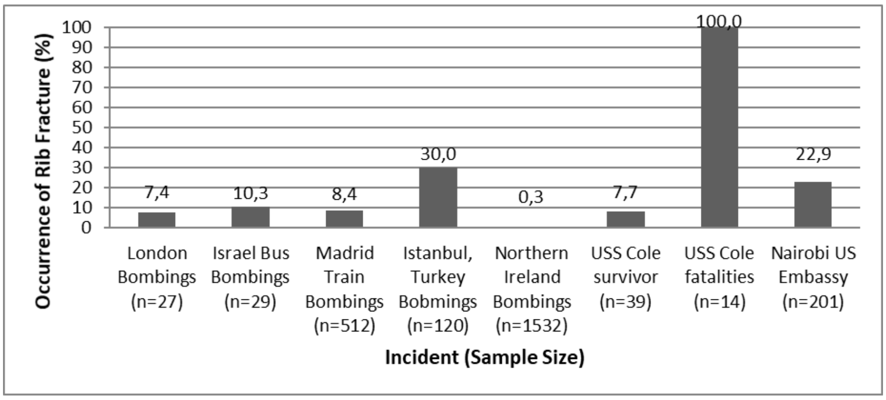

Figure 12.2: Percentage of rib fractures for each terrorist incident.

Continuing with the spine, vertebral fractures were reported in six incidents (6/13). The fatalities from the USS Cole bombing reported the highest incidence of vertebral fractures (71.4%), followed by Istanbul (11.7%). The Northern Ireland bombings reported the lowest (0.065%) (Figure 12.3).

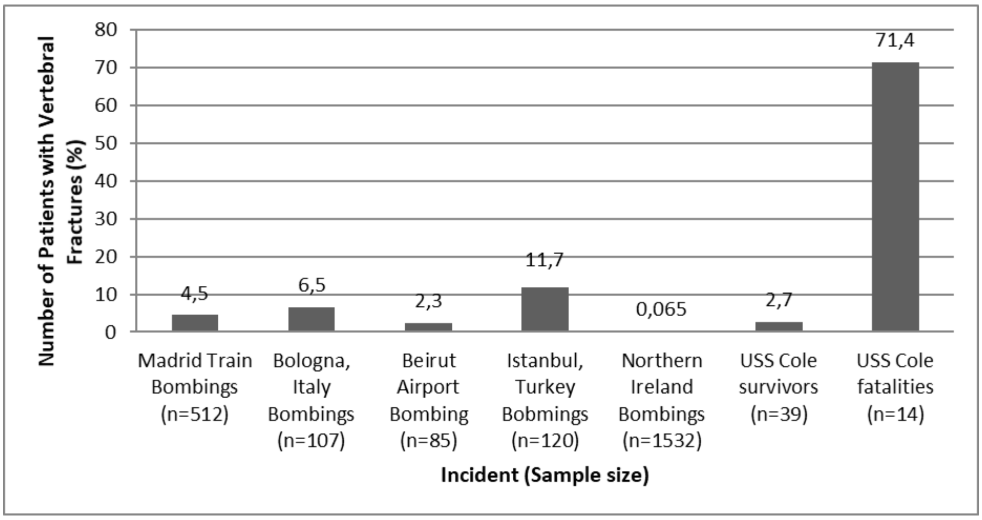

Figure 12.3: Percentage of vertebral fractures for each terrorist incident reporting the injury.

Twelve incidents (12/13) reported long bone injuries. The fatality population from the USS Cole bombing reported the highest prevalence (92.0%), followed by the bombings in Istanbul (42.5%) and Bologna (35.5%) (Figure 12.4). The lowest prevalence was reported in the Northern Ireland (0.92%) and the AMIA (5.5%) bombings.

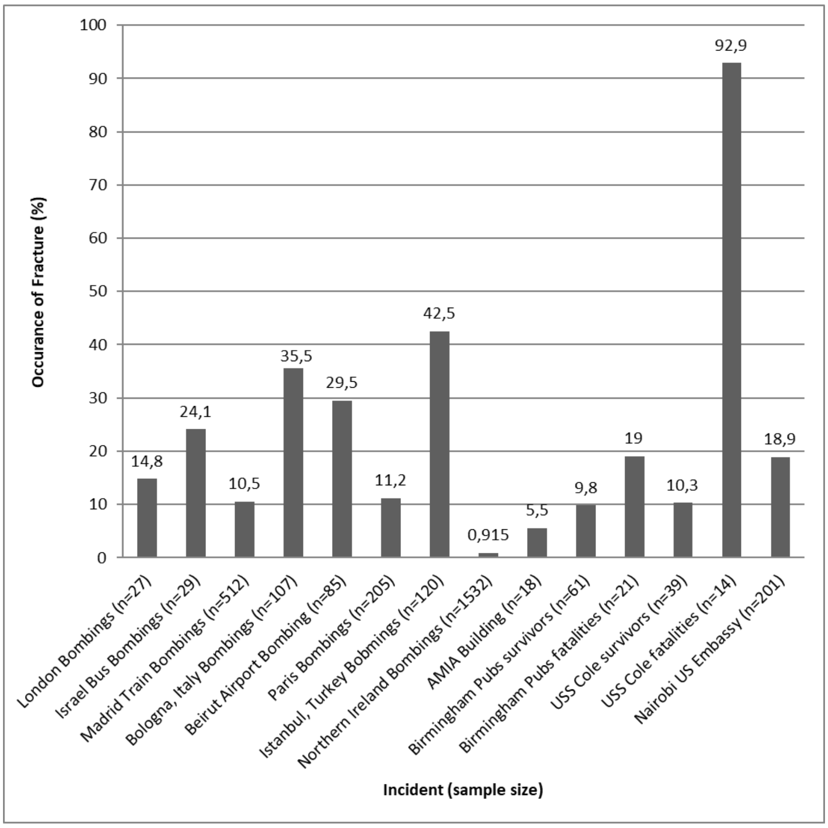

Figure 12.4: Percentage of long bone fractures in all incidents reporting the injury.

Eight incidents (8/13) reported the occurrence of amputations. The highest of these was the fatality data from the Birmingham Pub Bombings (43.0%), followed by the paediatric fatality population in the Oklahoma City Bombing (Figure 12.5). The lowest incidence was seen in Bologna, Israel, and Madrid with 2.8%, 3.4%, and 3.7% prevalence, respectively.

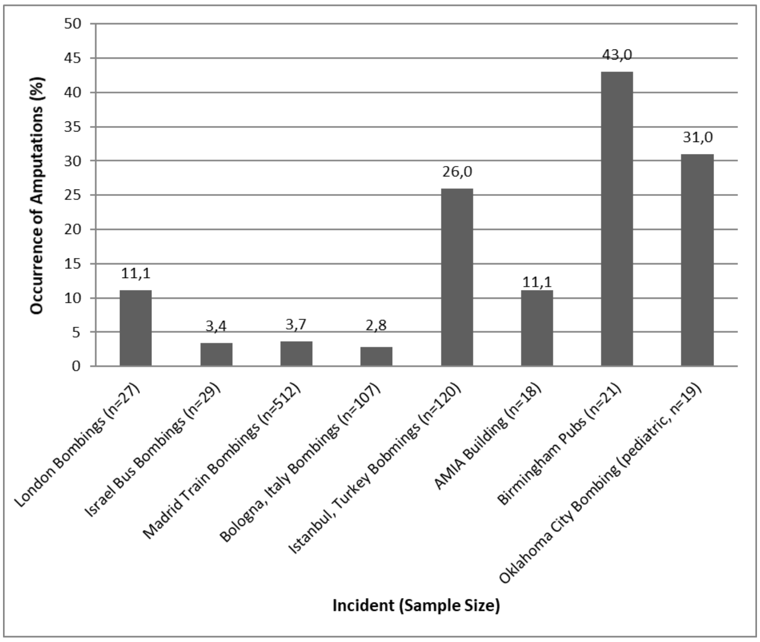

Figure 12.5: Amputations (including upper extremity, lower extremity, hands, and feet) across all incidents reporting the injury.

Figure 12.6 shows the average percentage of each injury type for the combined terrorism data, as well as 95% confidence interval (CI). The lowest average at 0.56% is metatarsal fractures, while the highest at 28.6% is non-specific limb fractures. The latter, however, also has a very wide CI. Amputations are the second highest at 10.5% with a moderately large CI, followed by skull fractures at 9.15 with a slightly smaller CI.

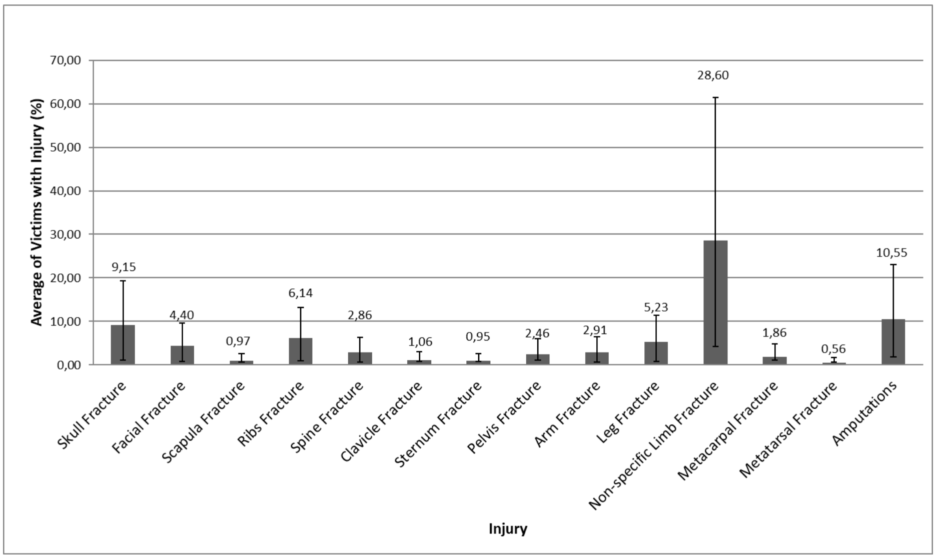

Figure 12.6: Injury types and average percentage of victims for all terrorism incidents.

Figure 12.7 represents data from combined terrorism events. The largest range and standard deviation between studies was seen in rib fractures (0.32% to 100.0%, SD 32.4). Non-specific limb fractures had the next largest range at 0.91% to 92.9% with a standard deviation of 22.9%. Skull fractures also had a large range, at 0.7% to 89.5%, but a slightly larger standard deviation than limb fractures at 26.3%. The lowest of these values was represented by metatarsal fractures with a range of 0.4% to 3.9% and a standard deviation of 1.9%.

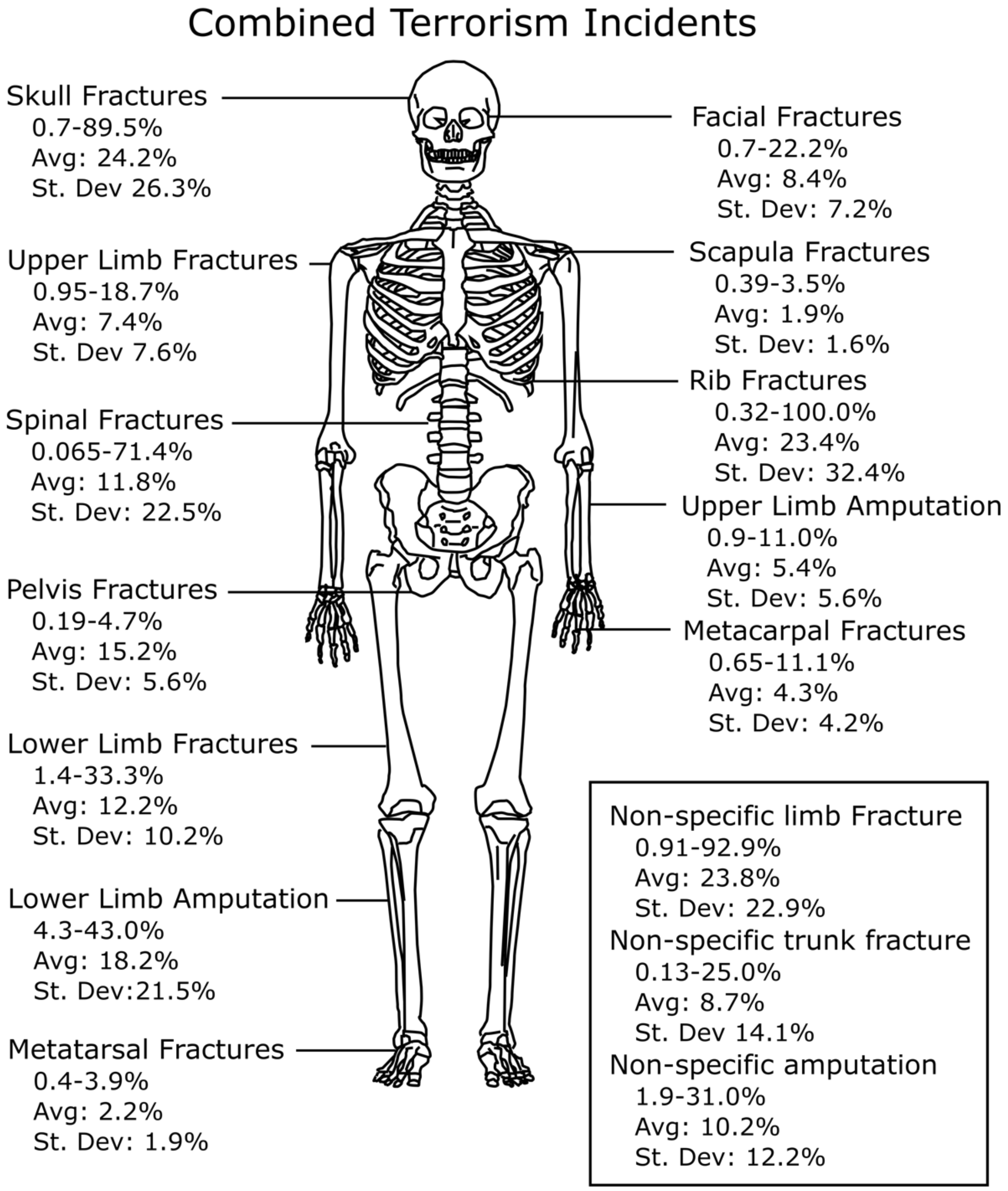

Figure 12.7: Data from combined terrorism incidents. Below each injury type is the range, average (Avg) and standard deviation (st. Dev).

4.1.3. Survivor Data versus Fatality Data

There were four sources that contained survivor-only data and five sources that contained fatality-only data. Skull fractures were reported in all of these. The presence of these fractures in the survivor data ranged between 1.64-11.6% of victims, the lowest being seen in the Birmingham Pub Bombings and the highest in the Beirut Airport Bombing (Figure 12.8). The presence of skull fractures in the fatality-only studies ranged from 28.4-89.5% of victims, with the lowest seen in the Nairobi US Embassy bombing and the highest in the paediatric group from the Oklahoma City Bombing (Figure 12.9).

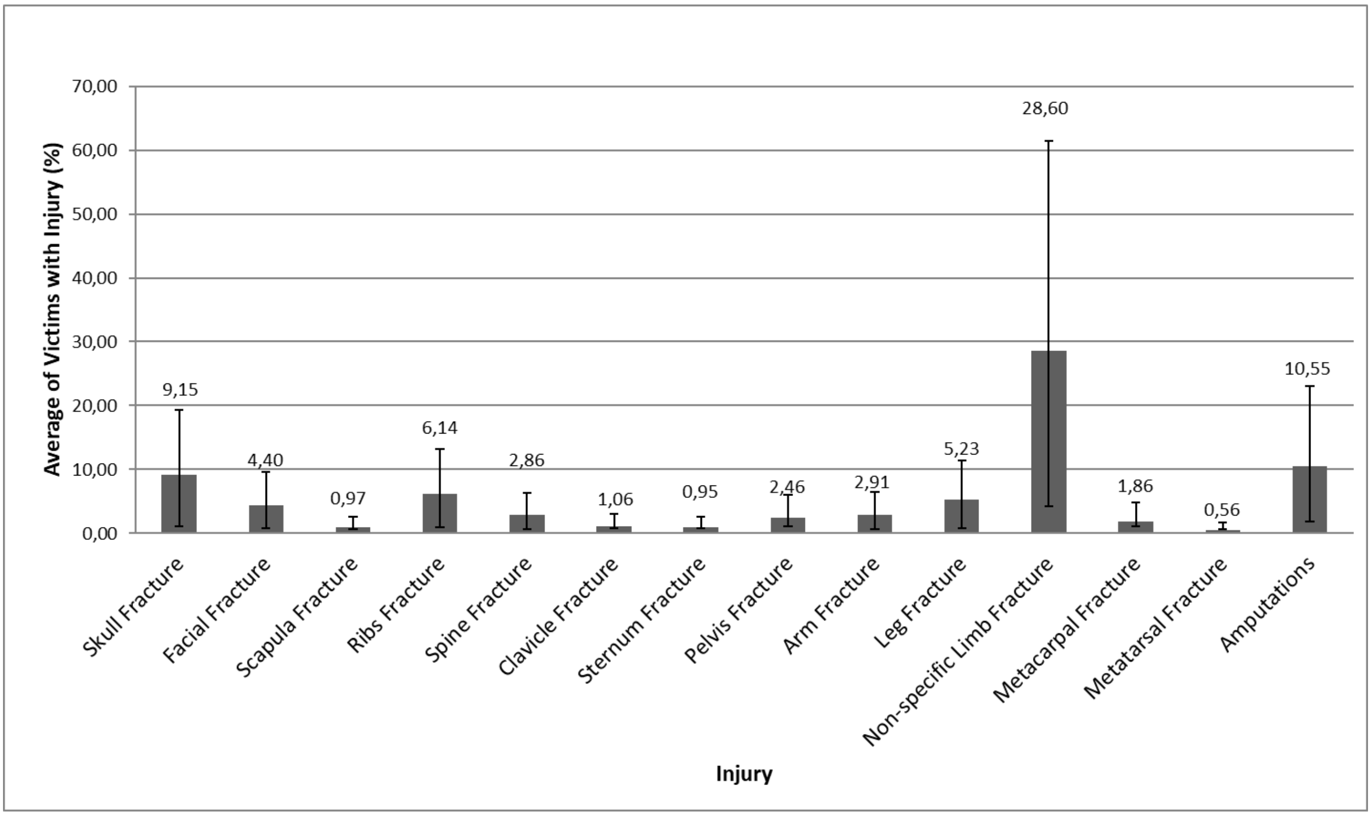

Figure 12.8: Percentage of skull fractures incidents containing survivor data only.

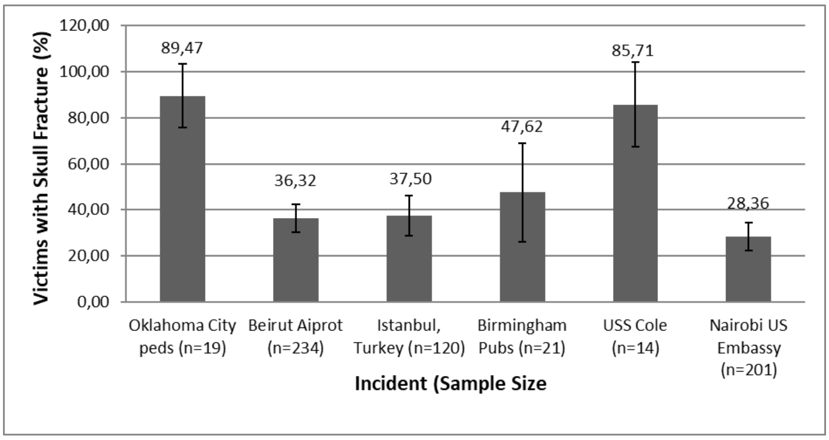

Figure 12.9: Percentage of skull fractures in incidents containing fatality data only.

For the three incidents that contained both survivor and fatality data (Birmingham Pubs, USS Cole, and Beirut Airport), odds ratios and confidence intervals were calculated. The odds ratio for the Birmingham Pub bombings was found to be 54.5 ($CI_{95\%}$= [6.32, 470]), suggesting that the ratio of skull-fracture to no-skull-fracture is approximately 54.5 times higher in the fatalities than the surviving victims. This trend continued with the USS Cole bombings, with an odds ratio of 228 ($CI_{95\%}$= [9.72, 5364.8]), and in the Beirut Airport bombings with 4.34 ($CI_{95\%}$= [2.30, 8.21]). The confidence intervals for all three incidents suggests significance.

5. Discussion

It is evident from these data that a representative picture of blast injury is not simple. The patterns are dynamic and will vary between and within incidents. This is because blast incidents are influenced by a large number of intrinsic and extrinsic variables, leading to significant variation in the expression of trauma (Palmiotto *et al* 2020). In addition, different modes of recording injuries and varying levels of detail also make analysis and interpretation difficult. There may even exist differences in the living versus the dead, as demonstrated by the comparison of skull fractures and survivability. While an understanding of the soft tissue trauma is quickly moving forward, investigation of the skeletal component of blast injury is slower particularly for anthropological purposes (Covey 2002; Kluger 2003; DePalma 2005; Institute of Medicine 2014; Christensen and Smith 2015). By examining descriptions of injuries observed in each incident, however, information about distribution becomes clearer, not only in what type of trauma is present but also in how it is reported.

The environment in which the explosive event occurs has been observed to influence injury and survival, specifically open versus closed environments (Kluger 2003). If there is an associated building collapse, this will also likely affect the distribution of trauma as crushing injuries will become more common (DePalma 2005). Distance from the blast, body position, explosive type, explosive amount, device design and orientation are also hypothesized to have an impact on injury profiles (Phillips and Richmond 1991; Wightman and Gladish 2001; Taber *et al*. 2006). The openness of the space will allow a large portion of the blast wave's energy to dissipate before reflecting off surrounding surfaces (Beveridge 2012). The amount of energy dissipation is more pronounced in an entirely open outdoor environment, though this is still subject to the geometry of the surroundings, especially in an urban environment (Smith and Rose 2006), while the ultra-enclosed environment such as an underground train has the potential to amplify the effects via reflection of the blast wave compared to other closed environments (Chaloner 2005; Cullis 2001). These changes in the physics of the blast wave are believed to directly affect injury, with many researchers reporting higher fatalities being observed in closed environments (Leibovici *et al*. 1996; Kluger 2003; Chaloner 2005). However, in a more recent study which reviewed 40 years of terrorist bombings, Edwards *et al* (2016), found there to be very little difference between death rates in closed and open environments, with there being slightly fewer deaths in the former. Similarly, there was little difference between numbers of injuries sustained in closed and open environments, although the frequencies of different types of injuries did vary. However, one of the author's (JR) experience seems to suggest that a higher number of fatalities can take place in ultra-closed environments.

When structural damage occurs after a detonation, victims not only exhibit primary injuries caused directly by the blast, but also an increase in secondary and tertiary injuries, specifically crush injuries—resulting from falling rubble (Mayo and Kluger 2006). In fact, the increasing use of vehicle borne IEDs (VBIEDs), suicide delivered IEDs and the deliberate addition of secondary fragmentation has also been recognised as a cause of an increase in secondary injuries (Kluger, 2003; Elsayed and Atkins, 2008; Mathews and Koyfman, 2015; Magnus *et al*., 2018). With regards to suicide devices, it is not just the added fragmentation (enhancements) that may result in this increase but also body parts from the suicide bomber themselves (Beaven and Parker, 2018; Delannoy *et al*. 2019). The terrorist bombings at the Bologna train station, the Alfred P. Murrah building in Oklahoma City, the Beirut Airport, the AMIA building, the Birmingham Pubs, and the Nairobi US Embassy Bombing were all associated with subsequent structural collapse. Though these injuries resulted from differing mechanisms, they were reported as all being from the same type of incident, associated with the explosion. While the clinical diagnosis of crushing injuries has clear signs differentiating mechanisms of injury, in skeletonized remains this is further limited

(Rajagpalan 2010). The Oklahoma City and AMIA bombings are particularly extreme examples of the scale of damage that can occur. These incidents reported skull fractures and 4 out of the 5 observed amputations, injuries that have been previously associated with high mortality in terrorist attacks (Okie 2005; Patel *et al*. 2012).

5.1. Injury Patterns by Anatomical Location

In this paper, we provide the following reports from the data gathered from more affected to least affected, with regard to skeletal remains. Thus, the list starts with the most frequently occurring skeletal injuries and perhaps providing higher diagnostic criteria for blast trauma.

Limb Fractures and Amputations

In the terrorist incidents, the most prevalent injury reported across all incidents was non-specific limb fractures, but this was associated with a large CI, suggesting wide variation in the presentation of prevalence of this type of injury. In contrast, the categories of upper limb fracture and lower limb fracture have much smaller associated CI, even though the type of injury is similar between these categories. Still, overall, the majority of these incidents of terrorism reported the occurrence of limb fractures. The only one not included—the Oklahoma City Bombing—mentions "limb fracture or dislocation" as a category of injury. This suggests the possibility that limb fractures were, in fact, observed in all incidents included in this study. A common occurrence was also noted in the military data included in this study, where 4 out of the 5 incidents reported limb fractures, supporting previous literature associating fracture of the extremities due to explosive munitions (Owens *et al*. 2007). Fracture type is reported predominantly as comminuted and may relate to the proximity from the explosion and therefore different types of blast injury (e.g. primary vs secondary) (Ramasamy *et al*. 2011). According to Christensen *et al*. (2012), comparing with gunshot and blunt force injury, fractures tended to be widespread and not have an identifiable point of impact.

Amputations and associated high mortality have been previously reported in both civilian and military blast incidents (Ramasamy *et al*. 2009; Patel *et al*. 2012), but the level of detail varies amongst publications. While some specified between upper limb and lower limb amputation, the majority only report "amputations", without specifying. Reporting also includes hands, feet, and even digits—the level/severity of which differs greatly among these. Other publications mention head amputation near the focus of the explosion (Sanabria and Rodriguez, 2016). Regardless of these issues, amputations were still reported in eight of the of the thirteen terrorism incidents and in 3 out of the 5 military incidents. Blast injury should therefore be considered as a mechanism when examining evidence of amputation or even missing bone elements, though further investigation is needed. One study from the Northern Ireland bombings that focused specifically on amputations described the fracture patterns at the amputation sites themselves, observing comminuted, spiral, segmental, and open joint fractures (Hull *et al*. 1994). However, device design and placement will have a significant impact. For instance, there may be more lower limb amputations in landmine explosions, but more cranial fractures in suicide bombers wearing backpacks. Gates *et al* (2014) theorised, for instance, that the lower mortality in the Boston Bombing was due to ground level, open air placement although the majority of injuries were secondary blast due to primary and secondary fragmentation.

Skull (neurocranium or cranial vault) Fractures

While skull fracture did not have the highest percentage overall in the terrorism incidents, it was reported in 12 out of the 13 events. While there is the possibility for bias here as head injuries usually require hospitalisation and could potentially be reported more often, its notable presence warrants further investigation of the relationship of skull fractures to blast and variables that could confound this (e.g. environment, structural collapse, mortality data). Skull fractures are mentioned in the military data in Fromelles, Korea, and Iraq. However, the occurrence of these fractures decreased from 79.5% at the Battle of Fromelles to 33.3% in the Iraq War. This could be due to the advancement of armour, particularly helmets, as well as changes in how the explosives were deployed (Tham *et al*. 2008; Moss *et al*. 2009). Basilar fractures were mentioned in the Madrid and London bombings and may indicate blast injury in closed environments; however this has only been discussed in two events in this data. Nevertheless, Sanabria and Rodriguez (2016) indicate that in the skull the most fragile bones are the most vulnerable such as the zygomatics, temporal squama; but also fracturing on ear ossicles (especially the incus) and transverse dental fracture may be present.

Rib fractures

Rib fractures were observed in over half (8/13) of the terrorism incidents, not including reports of "trunk fracture," or "thoracic fracture". Rib fractures have previously been suggested as a potential indicator of blast injury in the skeleton, particularly by a unique pattern of butterfly fracturing observed in the mid-shaft of the rib during experimental studies (Christensen and Smith 2013). The terrorism publications unfortunately did not report on the type of observed fractures.

The highest prevalence—100.0% seen in the USS Cole fatality data—appears to be an outlier. This could be due to the fact that the data set in question comes from deceased victims only, representing possible increased severity in the trauma seen. It is also the smallest sample size (n=14) out of all the incidents reporting rib fractures. The First World War, Second World War, and Korean War data all reported rib fractures, but the particularly detailed data on the modern Iraq War made no mention of the injury. This can potentially represent the impact of the use of body armour and armoured vehicles in modern warfare compared to previous conflicts (Gofrit *et al*. 1996; Gondusky and Reiter 2005; Lakstein and Blumenfeld (2005).

Facial Fractures

Facial fractures were reported in 8 out of the 13 incidents and some provided more detail as to the location of the fractures. The Bologna bombings and the Birmingham Pub bombings, for instance, both reported orbital fractures. The Northern Ireland bombings reported nasal fractures. Fractures to the face may be dependent on location of the explosive in relation to the victim and how they are standing as the force of the detonation would need to directly interact with the face (Wightman and Gladish 2001; Bhadani, *et al*. 2005). There may also be an interaction with varying atmospheric pressure affecting sinus filled areas (Agir *et al*. 2006; Thach *et al*. 2000). No facial fractures were specifically reported in the military data included in this project. Maxillofacial fractures have been reported in the military with IEDs as the mechanism before, but incident-specific data was unable to be recovered (Breeze *et al*. 2010).

Vertebral Fractures

Vertebral fractures were reported in 6 out of the 13 incidents, ranging from 0.06% to 71.4%. The higher end of this range (from the USS Cole fatalities) appears to be somewhat of an outlier for this data set, as the next highest prevalence is 11.7 from the bombings in Istanbul. This could be attributed to a variety of factors from sample size, to incident nature.

Pectoral, Pelvic Girdle and Sternal Fractures

Fractures to the scapula, clavicle, innominates, sacrum, and sternum have the lowest prevalence rates in and across all incidents. This is likely because they are very rarely reported, as our experience indicates that this can be prevalent, especially when blast comes from the floor; or alternatively when the remains are those of bomb carriers or suicide bombers (e.g. see Delannoy *et al*. 2019). In our study, only 2 incidents reported sternum and clavicle fractures, 3 for scapula and pelvic fractures. The presence of pelvic fractures specifically could be an indication that injuries sustained involved a particularly high amount of force, as it takes a great deal to disrupt the pelvic ring, for example in road traffic collisions (Falzarano *et al*. 2014).

Metatarsal Fractures

Metatarsal fractures were seen with the lowest average across all incidents at 0.56%. This is likely due to the fact that they were only specifically documented in two incidents. It is very possible, however, that these fractures are included in other incidents that discuss foot fractures or non-specific limb fractures. Military data, in particular the case studies from the Korean War, discussed the presence of shrapnel or fragmentation in the foot bones, hypothesized to have been imbedded at the time of the blast (Willits *et al*. 2015). Thus, apart from metatarsals, tarsal bones must be observed too, as these could have injury from blast (e.g. Commandeur *et al*. 2012).

The presence of metal fragments in the lower extremities should therefore be considered as a potential indicator for blast injury, in addition to possible device type and location (i.e. ground based or anti-personal landmine).

Overall, this pattern of skeletal fractures has similarly been described and summarised by Sanabria and Rodríguez (2016) who see the following evidence for blast trauma: long bone fractures, comminuted and oblique, scapula and pelvis affected, butterfly fractures on the rib, amputations whether of the fingers, hands or limb, metallic fragments of bone, especially in primary and secondary injury; with crush (blunt) fractures in tertiary, for example on vertebrae and ribs.

As highlighted earlier, there were a number of limitations and in particular for this discussion, a few to address. Bias is an important consideration in that the difference in fracture presentation between the living (injured/survivor) and the deceased (non-survivor) could be significant. For example, the amount of skull fractures in the survival data ranges from 1.65-11.6%, while the fatality data ranges from 28.4-89.5%, suggesting a much higher amount of skull fractures reported in the fatality data. Data from the Birmingham Pub Bombings, the USS Cole terrorist bombing, and the Beirut Airport Bombing report differences. In the Birmingham Pub Bombings, the odds ratio was calculated to be 54.5, suggesting that the ratio of skull-fracture to no-skull-fracture is that 54.5 times higher in fatalities than in survivors. The confidence interval, at 6.3-470.0 suggests the odds of finding a skull fracture in a fatality are significantly higher than in a survivor. This trend is the same across all three incidents, with USS Cole having an odds ratio of 228 and a confidence interval of 9.7-5364.8, and the Beirut Airport having an odds ratio of 4.3 and a confidence interval of 2.3-8.2. Thus, skull fractures are seen more often in the fatality population because they are associated with a higher mortality (Okie 2005). This is further supported in the military data with the incidence of skull fracture in Fromelles being relatively high at 79.5% from those who died in battle. The Iraq data also supports this, where skull fractures were seen in 55.5% of fatalities, but only 12.5% of survivors, though this was not statistically evaluated. As the anthropological population tends to examine fatalities, skull fracture prevalence could be an important indicator of blast injury when combined with other contextual factors.

Differentiating blast trauma from other types of trauma is possible, but it requires thorough analysis of the individual skeletal injuries and careful interpretation of the injury distribution over the entire skeleton in combination with contextual evidence. If blast injury is suspected, consideration should be given to bone type, injury location, and all available contextual and investigative information including the number of explosives utilized, the presence of potential projectiles, and the placement of the explosives in relation to the victim. High-velocity projectile trauma from gunshot wounds can often be distinguished from fragmentation trauma based on differences in size, shape, number, association, and distribution of wounds, with fragmentation wounds being more variable and irregular in size and shape and also more numerous (Kimmerle and Baraybar, 2008). The lower impact force of fragmentation compared with ballistically optimised projectiles also generally means that fragments will seldom exit the victim and are often recovered. Blast and high-velocity projectile injuries tend to differ on body region affected, distribution, and severity (Peleg *et al.*, 2004), and blast traumas involve a higher energy mechanism, leading to increased injury severity and more fractures compared with gunshot wounds (Weil *et al*., 2007).

6. Conclusion

Trauma analysis in anthropology tends to focus on three main categories: sharp, blunt, and ballistic. It is the combination of these injuries—whether viewed in one individual or in a set of several individuals—that are beginning to introduce a fourth category for differential diagnosis: blast injury. As Ramasamy and colleagues (2009) noted, fractures are the second most common type of injury reported in studies on recent conflict-related trauma. This emphasizes the need for forensic anthropologists to develop a better understanding of the skeletal component of blast injury. This is true whether it is at the excavation of a mass grave, when examining bone fragments after a major disaster, or when trying to discern what took the life of a recovered serviceman so that their family can better obtain a better understanding of the circumstances of their death

The forces associated with an explosion can cause damage to the skeleton, either directly from the forces of the blast wave and blast wind, or by -fragmentation, flying debris, and body displacement (Kluger *et al*. 2007). The variety of ways this could present in the skeleton include fractures, penetrating wounds, projectile wounds, amputations, and blunt force trauma. The pattern of how these appear is important in differentiating trauma caused by blast as opposed to other mechanisms. Based on the information ascertained, and especially the context in which the remains were found, forensic anthropologists should consider the following as potential signs of blast injury in the human skeleton, especially in combination:

- Skull fractures, including basilar fractures in closed contexts
- Facial fractures, with special attention to orbit fractures
- Limb fractures, particularly comminuted fractures, widespread and with no defined point of impact
- Evidence of amputation and/or missing bone elements
- Rib fractures, with special attention to butterfly fractures on the visceral surface (Christensen and Smith, 2013)
- Vertebral fractures
- Disruption of the pelvic ring
- Metal fragments imbedded in bone, particularly metatarsals and lower limbs

Due to the challenging distinction between gunshot wounds and blunt force trauma to blast trauma, and the differential diagnosis on these, it is important (Sanabria and Rodríguez, 2016: 671, 675) to examine the trauma traits with detail, examine the distribution of the injuries or patterns and an examination of any metal fragments, alongside the scene information and hypothesis to be tested.

Beyond retrospective analysis, experimental studies simulating these wounds must also increase, as that is the only way to have full control over recreating different types of “incident” and accounting for any confounding variables. The types of fractures and microscopic fracture patterns (e.g. see Pechníkova *et al.* 2015) would benefit from further investigation as they are rarely described in the current literature. Use of low and high-power microscopy, and Scanning Electron Microscopy (SEM), would enable the characteristics of fractures to be analysed in greater detail and the latter may also assist in the detection of small fragments of metal which are not visible to the naked eye. For forensic anthropology practices to remain current and as helpful as possible, blast injury must join the repertoire of anthropological trauma analysis.

Cases that may require the ability to discern blast trauma from other mechanisms include mass grave excavations (Baraybar and Gasior 2006), the recovery of remains of service personnel, and complex blast incidents involving civilians. The use of explosives in mass killings and genocide is not unheard of and should therefore not be omitted from consideration as a potential mechanism when examining trauma (Strippolo 2009). If there are bone elements missing from a grave, for example, it should not be assumed to be the result of taphonomy, poor preservation, or even commingling—it could be possible that the missing bone is a result of amputation by blast; or alternatively if there is an extra limb this could be from an amputation in a surviving casualty.

An anthropologist's ability to recognise blast trauma could aid in determination of cause of death, especially in Human Rights´ cases. Furthermore, where a forensic pathologist is required to provide as much information as possible and in order to help those investigating the incident (Mundorff *et al*. 2009), forensic anthropologists can assist too with physically reconstructing the fragmented remains to enable the former to interpret defects more easily. A deeper understanding of the injuries caused by the explosive event could lead to more information about the design and materials used and in turn, the perpetrator and their intent as well as potential counter-measures.

Further investigation should be carried out on the effect of structural collapse on injury interpretation, perhaps by directly comparing these injuries with other mass fatality events not involving an explosion. This once again highlights the need for more detailed recording of injuries. Overall, the study of blast injury by forensic anthropologists is still largely in its infancy. As it becomes more widespread, however, it is vital to the future of the discipline that the skeletal component of such injuries becomes better understood as to aid in identification and interpretation.

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