THE BLAST PELVIS

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DECLARATION OF ORIGINALITY

The work presented in this thesis is my own and all else is appropriately referenced.

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ABSTRACT

Decreasing the human cost of war is a vital role within the Ministry of Defence, and the Defence Medical Services. With the considerable improvements in care, from point of wounding to rehabilitation, it is possible that we have reached the ceiling of optimal management with available, deployed resources. Injury prevention or mitigation may therefore have a more important role than ever in improving survival rates.

The current character of conflict, and certainly the recent conflicts in Iraq and Afghanistan have seen the Improvised Explosive Device used to devastating effect to personnel. These devices cause multisystem injuries, and have a high fatality. The lower extremity was most often affected in these recent conflicts, and many fatalities occurred. A greater understanding of lower extremity injury biomechanics is likely to be key to preventing future fatalities in this body region.

This thesis focusses on lower extremity blast injury, performs a review of current understanding, and undertakes a casualty data analysis to further understand injury patterns and the cause of fatal wounding. This analysis finds that haemorrhage secondary to pelvic fracture is the key factor in fatal lower extremity injuries, and therefore an area of considerable research interest. Pelvic injury patterns were therefore analysed using measurement techniques to qualify injury patterns and understand the link between injury patterns and the presence of vascular injury. Subsequent physical and computational testing provided a platform to apply different loading conditions to the pelvis to replicate a blast injury, and understand the behaviour of the bony structures under high rate axial loading.

This thesis concludes that the anterior pelvic ring at the pubic symphysis is key to pelvic integrity at high rates of loading. Disruption of the anterior pelvis can lead to subsequent posterior ligamentous rupture which, due to the proximity to major vessels, can lead to major haemorrhage and death. Preventing lateral disruption may be the key to maintaining pelvic integrity at these high loading rates, and preventing vascular compromise and fatality from lower extremity blast injuries.

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ABBREVIATIONS

Abbreviation	Explanation
AIS	Abbreviated Injury Scale
AnUBIS	Anti-vehicle Under Belly Injury Simulator
AKA	Above Knee Amputation
ARDS	Acute Respiratory Distress Syndrome
ASIS	Anterior Superior Iliac Spine
ATD	Anthropometric Test Device
APM	Anti-personnel Mine
AVM	Anti-Vehicle Mine
BKA	Below Knee Amputation
BMI	Body Mass Index
CAT	Combat Applicator Tourniquet
CBIS	Centre for Blast Injury Studies
CT	Computed Tomography
DC	Defence Clothing
DCA	Defence Consultant Advisor
DE&S	Defence Equipment and Support
DMS	Defence Medical Services
DOW	Died of Wounds
DSTL	Defence Science and Technology Laboratory
EFP	Explosive Formed Projectile
FEA	Finite Element Analysis
ICC	Intra-class Correlation Coefficient
GCS	Glasgow Coma Scale
HE	High Explosive
HSV	High Speed Video
IED	Improvised Explosive Device
KIA	Killed in Action
ISS	Injury Severity Score
JTCCC	Joint Theatre Clinical Case Conference
JTTR	Joint Theatre Trauma Registry
JTTS	Joint Theatre Trauma System
LE	Low Explosive
Mil-Lx	Military Lower Extremity (testing surrogate)
MOD	Ministry of Defence
MRI	Magnetic Resonance Imaging
MTC	Major Trauma Centre

NATO	North Atlantic Treaty Organisation
PACS	Picture Archiving and Communication System
PCE	Personal Combat Equipment
PI	Pelvic Injury
PF	Pelvic Fracture
PMHS	Post Mortem Human Specimen
PMCT	Post Mortem Computed Topography
PMMA	Polymethyl Methacrylate
PPE	Personnel Protective Equipment
PS	Pubic Symphysis
RCDM	Royal Centre for Defence Medicine
RCDR	Royal Centre for Defence Radiology
RSI	Rationalisation, standardisation, interoperability
SID	Side Impact Dummy
SIJ	Sacroiliac Joint
TA	Traumatic Amputation
THOR	Test Device for Human Occupant Restraint
TKA	Through Knee Amputation
TNT	Trinitrotoluene
UBB	Underbody Blast
WIA	Wounded in Action
WIAMan	Warrior Injury Assessment Mannequin

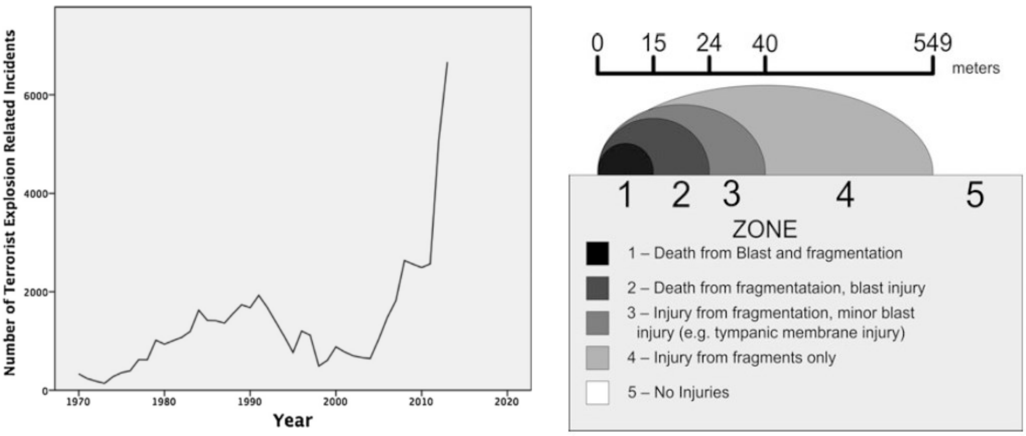
CHAPTER 1

INTRODUCTION

The incidence of destructive injuries has been prolific in the 10 years of war in Iraq and Afghanistan, a conflict dominated by injuries due to explosives, particularly the Improvised Explosive Device (IED). Injuries secondary to explosives cause multisystem injuries, and have a high fatality rate. Analysis of injury patterns in these casualties offers a further understanding of the behaviour of the body under blast loading, and with this understanding, proposals for methods in which to improve outcomes can be made. This PhD thesis aims to explore lower extremity wounding, in which a detailed knowledge of injury patterns could have a substantial effect on increasing survivability from explosive methods in warfare.

1.1 Overview

The recent conflicts in Iraq and Afghanistan saw the widespread use of the IED as the predominant mechanism of wounding (Edwards and Clasper 2016). These devices cause significant injury to multiple body regions, and have a high mortality rate (A. Ramasamy, Hill, and Clasper 2009). Those patients that do survive often have treatment that is lengthy and complicated requiring multiple interventions, and a protracted recovery with rehabilitative challenges. The prevalence of explosions as a weapon of war, both in organised conflict and insurgent activity, in addition to residual legacy landmines and unexploded ordinates, mean that explosive incidents are still occurring in many parts of the world. The incidence of such events has also increased rapidly in recent times (Edwards et al. 2016) (Figure 1.1a). These complex and chaotic events are diverse, and their characteristics and efficacy depend on a variety of factors, such as charge size, embedded fragments, surrounding soil and dust, the location of the casualty at the point of injury, (Figure 1.1b) and whether in in an open or enclosed space.



(a) (b)

Figure 1.1: (a) The increasing incidence of explosive events worldwide (Edwards et al. 2016) (b) Zones of injury (metres) and blast characteristics.

Analysis of these events is challenging due to the multifactorial effects of explosions, however, learning more about how blast affects human tissues has important implications for treatment and prevention. Analysis of the casualty dataset in Iraq and Afghanistan enables a high volume of a similar demographic of trauma patients with a similar mechanism of injury and treatment pathway, to accurately map injury profiles and analyse the mechanism of blast injury. It is vital that this large dataset is interrogated thoroughly to ensure all opportunities are taken for improvements in clinical outcomes.

1.2 Research Focus

It is known that the majority of war injuries are to the upper and lower extremities (Bušić et al. 2006) due to their often closer proximity to the weapons systems, and their relative vulnerability, as they are not always protected to the same extent as the torso and head (Owens et al. 2008a). Lower extremity injuries are more likely to be fatal, and in the absence of injuries to other body regions, the majority of lower extremity injuries are due to exsanguinating haemorrhage (Mamczak and Elster 2012). It is known that major haemorrhage has been deemed to be a potentially preventable cause of death, and indeed, bleeding is responsible for the majority of potentially preventable fatalities (Hodgetts et al. 2007). Therefore, this thesis focusses on the lower extremity and fatal wounding, in an effort to understand injury patterns, causes of fatality, and how outcomes can be improved with a detailed retrospective analysis of the historical data. It is known that the 'signature injury' of the recent conflict included the triad of traumatic amputation, perineal injury and pelvic fracture, and that it was a highly fatal wounding pattern (Jacobs et al. 2014). However, no detailed analysis has yet occurred isolating the cause of fatality in these casualties and how such a severe injury could be mitigated.

1.3 Aims

The aims of this thesis are to:

a) Understand blast injuries, both mechanisms of wounding, and recurring patterns of injury in warfare;
b) Interrogate the lower extremity data to understand the areas responsible for fatal wounding in this body region;

c) Focus on the fatal wounding and provide a detailed review of injury patterns leading to mortal injuries;
d) Perform physical testing and computer modelling of these injuries to further understand how blast load affects human tissues;
e) Based on the models propose injury mechanisms and potential mitigation strategies with regards to preventing fatality in lower extremity blast injury.

1.4 Thesis Structure

Chapter 1 has provided a brief introduction and context to the research, and identified ongoing clinical questions important to reducing potentially preventable fatalities in lower extremity war injuries.

Chapter 2 discusses the literature surrounding human anthropology and the history of war, and the development of blast weaponry. It discusses the different elements of blast injury in detail, and their subsequent effects on human tissues. It concludes with an analysis of body region data confirming that the lower extremity is the most common body region to be injured, and has been shown to be a region with potentially preventable fatalities.

Chapter 3 presents data on the lower extremity injuries in Iraq and Afghanistan, and the outcomes of these injuries. It focusses on traumatic amputation as the most destructive of these injuries, being responsible for the majority of fatalities in this cohort. The existence of a pelvic fracture was shown to have the most impact on survival rates, and was therefore chosen as a focus of interest.

Chapter 4 describes severe pelvic fracture in both civilian and military contexts, presenting the diagnosis and management of high energy pelvic injuries. It concludes by recognising current gaps within the existing literature concerning blast injuries to the pelvis.

Chapter 5 describes a data analysis of the casualties sustaining pelvic fracture due to blast in the conflicts in Iraq and Afghanistan. It presents injury patterns, links specific patterns with the risk of fatality, and presents the differences in injury types depending on the environment at the time of the blast incident.

Chapter 6 presents a quantitative method of measuring the disruption in pelvic fractures, focussing on regions found to be important in the data analysis. It relates this measuring technique (in terms of direction and magnitude of pelvic displacement) to the presence or absence of vascular injury.

Chapter 7 presents a novel cadaveric testing method to simulate pelvic fracture in the dismounted casualty, and the data acquired through this testing were used to further refine the mechanistic hypotheses presented throughout this thesis.

A novel Finite Element Analyses (FEA) is presented in Chapter 8. Two pelvic models were created; the first including the vasculature to assess how and where vessels may be prone to rupture in various pelvic disruptions. The second reproduced the physical experiments, and subsequently produced different loading patterns that may lead to the pelvic disruptions seen in blast.

The conclusions to this work are presented in Chapter 9, which includes summaries of the novel findings of this research, and applications in clinical and military practice.

CHAPTER 2

LITERATURE REVIEW: WAR INJURIES

This chapter analyses the patterns of war injuries throughout history, and the recurring problems faced by clinicians managing those injured by way of the destructive mechanisms encountered in armed conflict. It subsequently focuses on the more recent clinical challenges from injuries due to explosives, and how the different factors that make up an explosive event affect human tissues. The different subcategories of blast are explained, and the burden of blast injury in modern conflicts presented. In particular, more recent injury patterns in the conflicts in Iraq and Afghanistan are described, and a focus for further research and improvement is proposed.

2.1 Introduction

2.1.1 A Brief History of War

Infliction of physical injuries towards humans, by other humans, is documented widely in literature and archaeological specimens dating back to the most ancient of human civilizations of 10,000 BC, of which there are countless examples of ritual killings, human sacrifice, cannibalism and warfare (Martin and Frayer 2014)(Figure 2.1). The reasons for interpersonal violence and mass killings within social groups are varied, and are speculated to include religious and cultural beliefs, political and ideological factors, demographic stresses and gender based conflicts.

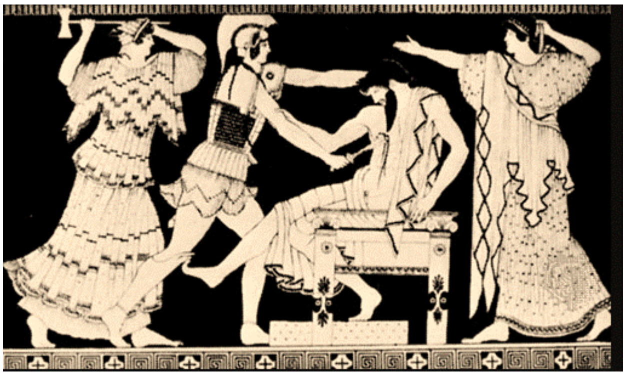
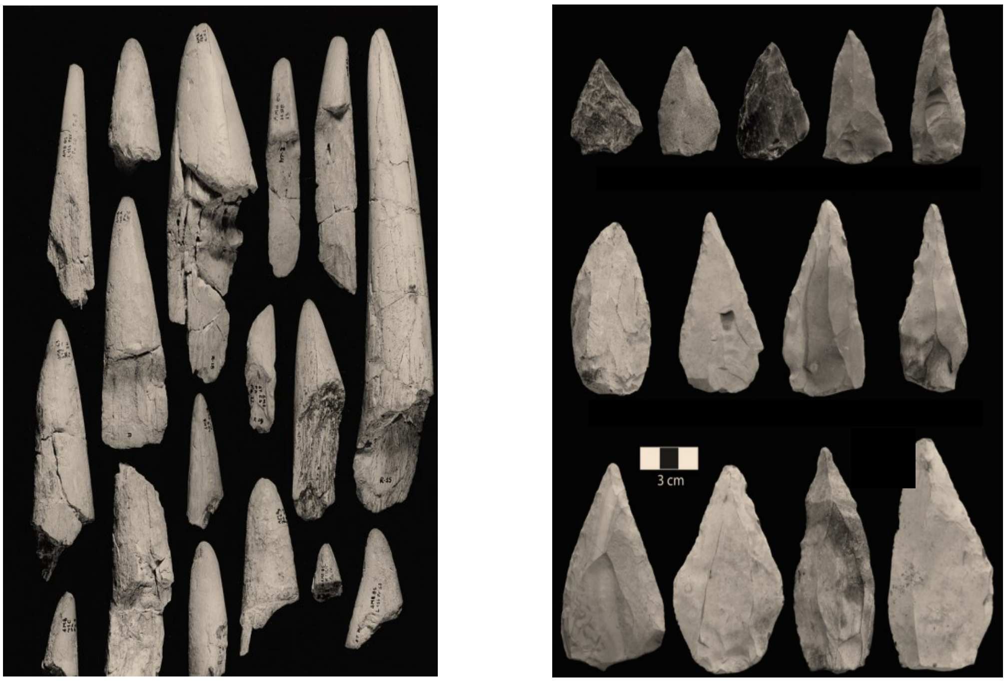


Figure 2.1: Electra and Orestes performing the ritual killing of Aegestus in Greek mythology. Adapted from (Encyclopedia Britannica 2010).

Organised warfare on a larger scale later occurred between differing social groups, and the causes for this are much debated by anthropologists, but include competition for land and resources, religious differences and fear (Milner G, Anderson E 1991). Organised warfare between these differing social groups became the primary influence in organizationally complex societies, and this remains the case in modern conflict today (Vaughan-Williams 2008). It is much debated as to whether conflict is an intrinsic part of human nature and is necessary for evolution and societal development, and whether striving for a world without violence is out of the realms of possibility (Cohen and Insko 2008). However, based on the widespread prevalence of violent behaviours towards individuals and groups worldwide at the time of writing, it can be reasonably assumed that injury due to conflict will continue to occur in the foreseeable future, and therefore understanding weapons systems and injury mechanisms will continue to be crucial in order to limit fatalities (Ministry of Defence 2015).

2.1.2 The Evolution of Weapons Systems

Weapons are among man's oldest and most significant artefacts, and have become more complex as human civilisation has developed. The acquisition of weapons has been proven to have been a significant evolutionary advantage, and therefore, proliferation of weapons has thrived throughout the ages (Wilkins et al. 2014). Weapons have transformed over thousands of years from weapons used in hand to hand combat to inflict damage to individuals, to the more extensive explosive weapons systems of modern times, producing casualties in greater numbers. Establishing the first use of weapons is a complex task for historians and archaeologists, as initial items were likely to have been constructed from perishable materials, for example wood, or stones or rocks, not recognisable as weapons (González-José and Charlin 2012). Weapon 'points' that have been attributed to killing are the earliest known artefacts of prehistoric times in existence which have survived for analysis (Figure 2.2). These would have been used for hunting animals for food, however, embedded points in human archaeological remains demonstrate their use in human to human combat, and would have been handcrafted in bone, antler, ivory or stone (Knecht 1997; Villa and D'errico 2001). These points were crafted with attention to fairly sophisticated knowledge of geometry and flight, with points distinguished from each other by weight and shape, depending on whether they were intended for close range use, or to be thrown (Thomas 1978). These weapons depend on being at close range to prey or victim, meaning that hunting posed a considerable risk to life. Therefore weapons were later developed to be used at longer range, in the form of bows and arrows, and crossbows (a horizontal version which could be preloaded, allowing for greater accuracy), which were developed initially in ancient China (DeVries and Smith 2012). Such implements were examples of the first projectiles, and were used throughout medieval history for culling prey, and in warfare.



(a) (b)

Figure 2.2: Archaeological points in ivory (a) adapted from (Villa and D'errico 2001), and (b) stone (adapted from (Wilkins et al. 2012).

The requirement of weapons to penetrate fortifications (to overpower towns and cities) meant that weapons systems had to increase in their destructive potential (DeVries and Smith 2012). The first 'recipe' for gunpowder was thought to have been published as early as 1044AD, again in China (Partington 1999). However, the term 'gunpowder' covers that of both a material designed to burn, and that of a propellant pyrotechnic or explosive, (the specifics of these individual terms are described later in this chapter (section 2.2.1)). For this role a ready supply of oxygen is required. Atmospheric oxygen is not enough to cause the rapid expansion of gas required as an explosive, therefore nitrate salts were employed for this function within the substance itself. These nitrate salts were referred to collectively as 'saltpeter' the oxidising component of gunpowder which, combined with sulphur and charcoal, completed the mixture. The discovery of this compound lead to the development of cannons, initially as flame projecting, and later as missile projecting, in order to launch projectiles to traverse ground and injure buildings or personnel. This was termed 'artillery' (meaning, weapons beyond the reach of small arms fire). Around the same eras and using similar technology, smaller hand held devices were created, and these were the first firearms.

It was later discovered that these explosive compounds containing rapidly oxidising gunpowder could be used in their own right. As compounds were developed to have more stable characteristics, explosive compounds were then packed into ammunition 'shells' which could then be fired or dropped, as the first 'bombs' (Beveridge 1998). These devices have further developed into precision guided missiles to improve accuracy. In addition to weapons of war, explosives are used in mining and civil engineering, and thus their use spread throughout the globe to propel development and innovation. Some have even described the development of explosives as the major trigger for advances in technology, science, economics, and politics to form and shape civilisation as we know it today (Buchanan 2006).

The efficacy of a weapon can be described in terms of magnitude of effect, accuracy, reach and mobility (O'Connell 1991). Development of new weapons systems are expected to exceed the capabilities of the previous, and are designed to be effective, and accurate. Nowadays, weapons must comply with international regulations, and within the United Kingdom and throughout the world, weapons systems are required to comply with North Atlantic Treaty Organisation (NATO) standards in terms of rationalisation, standardisation and interoperability (RSI) (Taylor 2017). Despite this, non-state actors outside countries bound by international agreements do not necessarily comply with international regulations, and weapons systems are created using whatever means possible. Explosive devices of recent times exist in various forms. As well as offensive weapons, devices can be used for defensive means, to deny ground, for example, in the development and utilisation of mines.

Landmines, Anti-personnel and Anti-vehicle mines

Blast land mines are static devices employed to protect and distinguish equipment and boundaries, and are a method of employing military force without the valuable manpower resource (Galbraith 2001). These devices have been in active use throughout the 20th century, and many remnants of landmine existence still occurs worldwide (Tremblay 1998). The countries with the highest number of casualties from this type of explosive are Afghanistan, Cambodia, Columbia, Myanmar, Cambodia and South Sudan, and it is reported that there are 12 incidences of landmine injuries per day worldwide due to remaining landmines, many of which involve children, as they are incidentally discovered in local terrain (Duttine and Hottentot 2013). Landmines are designed as a deterrent, although injury to people and equipment does occur. Specific devices designed to act against vehicles: anti-vehicle mines (AVMs) and personnel: anti-personnel mines (APMs) were subsequently designed for those purposes. The first use of both AVMs and APMs was in World War 2. AVMs were the first to be introduced, and have been reported to be the leading cause of vehicle loss throughout this era (Bird 2004). The smaller APMs were subsequently designed in order to prevent enemy interference with the larger AVMs (McGrath and Stover 1991). The main differences between these devices is weight, and anti-vehicle mines are designed to trigger at a larger weight, as to not expend the device on smaller, less strategically important targets, like individual personnel. In all categories of mines, integration with their environment potentiates their effects. These devices are usually buried under the ground to go initially undetected, and this means that soil, dust and debris become projectiles and contribute to the injury process. There are global calls to eradicate these devices, which are destructive and indiscriminate, and as a result, do not conform to international laws. Landmines are commercially produced, but their use in recent years has diminished due to international agreements and legislation (Moody 2008). However, with the reduction in standardised mine use, there has been an increase in the use of non-commercial, locally produced explosive devices, as typified by the use of IEDs, particularly in recent conflicts in Iraq and Afghanistan, but also increasing incidences throughout the world.

Improvised Explosive Devices

IEDs have become the weapon of choice for many terrorist organisations who may not have access to traditional weapons, and therefore create handmade devices from accessible materials. Non-regulated and non-standard, these devices have unpredictable effects. They are often termed ‘victim operated IEDs’ due to the casualty inadvertently triggering the weapon (U.S. Army Combined Arms Centre 2009). IEDs are classified as devices that use modified conventional or unconventional weapons to achieve their effect. Examples of IEDs might include car bombs, pipe bombs, and suicide bombs. These are often impregnated with bolts, glass shards, nails or other sharp implements, to cause additional trauma. In addition, burying devices beneath the ground not only aids in their non-detection prior to detonation, but as in mines, the products of the soil and surrounding environment contribute to fragmentation effects, and also introduce biological material from bacteria present within the local flora (Wightman and Gladish 2001). In order to understand the injuries caused by such weapons, it is important to consider the basic science behind these explosives.

2.2 Explosives as a Weapon of War

2.2.1 Background

An explosive is a chemical compound, either a solid or a liquid, containing potential energy, which can be subsequently released to create a substantial volume and pressure change to the surrounding environment (Singh et al. 2016). Mines and IEDs are examples of such weapons. Explosives are part of a range of materials known as ‘energetic materials.’ This includes propellants and pyrotechnics. The difference between propellants, pyrotechnics and explosives is the speed of reaction time, and the resulting pressure changes on the surrounding environment. Propellants are materials which burn to produce gases that cause motion when directed, for example, gunpowder (black powder) or gasoline. The reaction process is relatively slow, aiming to produce heat (in the form of hot gases) and therefore thrust. This differs from explosives and pyrotechnics by the rate at which the reaction occurs, and relatively insignificant surrounding pressure changes are observed. Pyrotechnics are materials that react rapidly, much more so than propellants, but differ in their mechanism to explosives by inducing only minor pressure changes in their surrounding environment. They are designed to produce smoke, light or heat, and are often combined with a propellant in order to drive the reaction remotely from its activation point. Examples of their use includes flares and fireworks. The key feature to identify a substance as an explosive is the extremely rapid timeframe in which energy is released – much faster still to that of pyrotechnics. For example, for a common use explosive, tri-nitro toluene (TNT) release, speeds can reach up to 8mm/µs, or 8km/s (Cullis 2001) (Artero-Guerrero, Pernas-Sánchez, and Teixeira-Dias 2017). All three classes of energetic materials can also be classified in terms of High Explosives (HE) or Low Explosives (LE). Low explosives are substances which combust rapidly to produce heat, known as deflagration, which is another word for ‘burning rapidly.’ Propellants are classed as LEs. HEs react much more quickly, and require a detonation to occur. This allows these potentially destructive materials to behave in a relatively inert fashion until triggered (detonated), which enables their safe handling and transport (Scott et al. 2006). Pyrotechnics and explosives are both classed as HEs.

The basic chemical components involved in an energetic material are a fuel, an oxidiser, and with HEs, a rapidly igniting material to induce detonation (Akhavan 2011). In order to classify as an explosive material, the resultant increase in pressure must exceed the size of the original explosive material. High explosives also require mechanical confinement, for example in a sealed container, to detonate. This allows pressure to build exponentially until the container shatters and the device explodes (Chidester, Tarver, and Garza 1998).

2.2.2 The Physics of Explosive devices

Understanding the effects of blast injuries on human tissues first requires a thorough understanding of the more detailed physics behind explosive events. The sequence of events in explosives is known as the 'explosive train,' and takes place in a sequence as follows beginning with detonation of the substance (Figure 2.3).

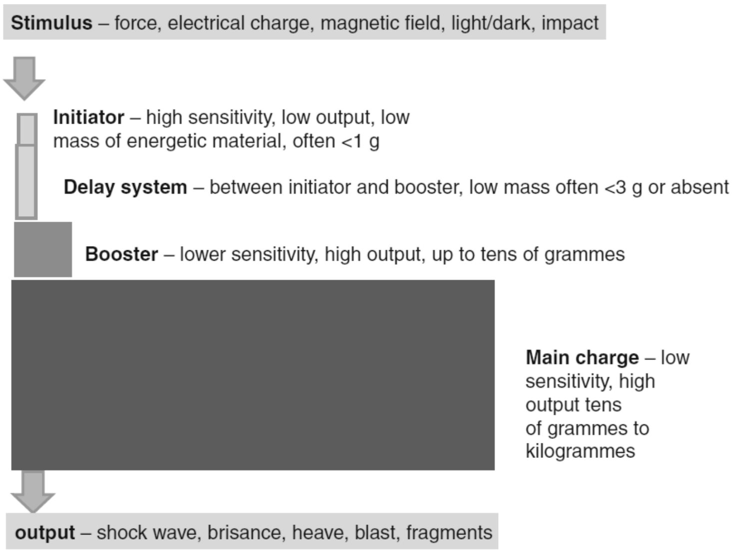


Figure 2.3: The Explosive Train. Adapted from (Bull, Clasper, and Mahoney 2016).

Detonation

Detonation is the process required to initiate the reaction of a HE (pyrotechnic or explosive). LEs (propellants) do not require a detonation, as they are designed to burn slowly (deflagrate), utilising oxygen. All LEs contain oxidising agents mixed with their fuel base, as well as utilising free oxygen in the surrounding environment. HEs require a quicker reaction process than LEs to produce their rapid effects, and to exert this, they do not require oxygen. Detonation within a HE is the process by which the chemical bonds in an explosive material are broken, creating a subsequent rapid energy release, by an initial stimulus (Cullis 2001)(Figure 2.3). The method used for denotation is usually another explosive material, which propagates its way through the main explosive, generating heat and causing energy release. Initial products of detonation must be separated in the first instance, to avoid explosives being triggered before desired. Therefore, the initiation of this detonation is usually a trigger, or button, by which detonating substances are mixed on demand, beginning the chemical reaction to produce heat. It is important that the volume of trigger material is kept low, and the trigger for combining this with the main device are kept separate; this creates a device that is stable enough for the operator to handle and transport, without the risk of unwanted and untimely detonation. A delay system is often introduced into devices to enable a device to be thrown, or the operator to escape the vicinity, although delay systems are not routinely employed. The process by which the chemical reaction in detonation traverses the explosive material is termed the *detonation wave* and for high performance explosives, the speeds of the detonation wave (detonation velocity) can reach 8km/s.

Propagation

Propagation occurs as the detonating explosive material, having travelled through the main explosive charge, compresses the explosive material generating heat. As heat is generated, a chain reaction occurs, whereby further bonds are broken, further energy is released, and the event becomes self-perpetuating. The relationship between the rate of reaction and the temperature of the materials is exponential, with each rising with continuation of the explosive process (Draeger, Barr, and Sager 1946). As the explosive material expands, oxygen molecules are introduced within the structure, further feeding the production of heat and flame (Nutaro, Seal, and Sulfredge 2017). Temperatures within explosions can reach up to 7000°C (Brode 1959).

Blast Wave

The blast wave consists of two components: a pressure wave initially, followed by a blast wind. The type of pressure wave that exists in blast is known as a shock wave, due to attaining supersonic velocity. The speed with which the changes to pressure, heat, velocity and density occur mean that the fast moving higher pressure regions in the wave interact with the slower regions, pulling them along and propagating the wave further accelerating it. This maximum level of pressure the shock wave achieves is called the peak overpressure. Following this peak overpressure, a rapid subsequent decrease in pressure occurs, with a resulting negative pressure void (Wolf et al. 2009). The sequence occurring in a blast wave is known as the Friedlander Wave Form (Figure 2.4)

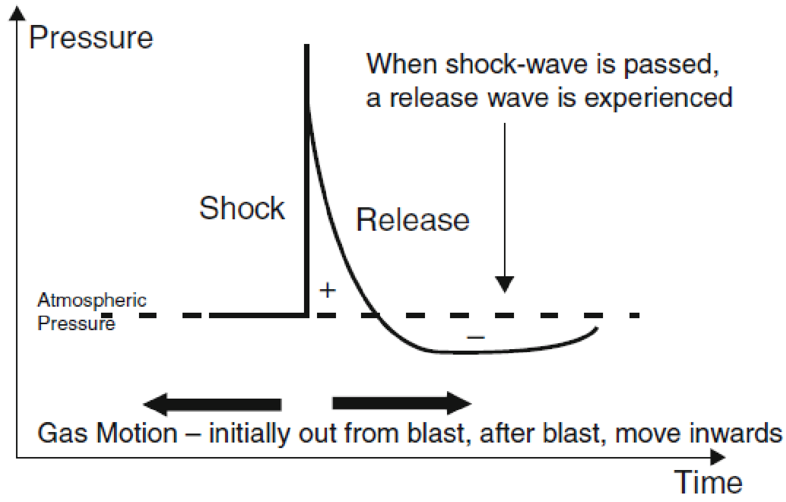


Figure 2.4: The Friedlander Wave form. Reproduced with permission from (Proud 2013).

A following 'blast wind' follows the pressure wave changes to fill the void created which acts as a vacuum, and can bring with it the explosive shell particles, dust, soil and surrounding debris which can act as secondary projectiles. Pure blast events are rare, examples of which are unburied anti-personnel mines and fuel air explosives (Dearden 2001). These blast waves dissipate the further the individual is away from the blast, and therefore efficacy relies on close contact with victims. The majority of effects from explosive injuries are from the fragmentation effects, but there are many factors contributing to overall injury burden.

2.2.3 Explosives and Human Tissue Trauma

Blast injuries can be categorised in their effect on body tissues in terms of primary, secondary, tertiary, and quaternary mechanisms (Zuckerman 1941)(Mayo and Y 2006)(Figure 2.5). In reality, few subjects are exposed to these categories in isolation, and most casualties sustain a combination of injury types. However, these terms help to compartmentalise the chaotic sequences within an explosive event, and with this knowledge, helps to piece together understanding in terms of pathophysiology, treatment implications and prevention.

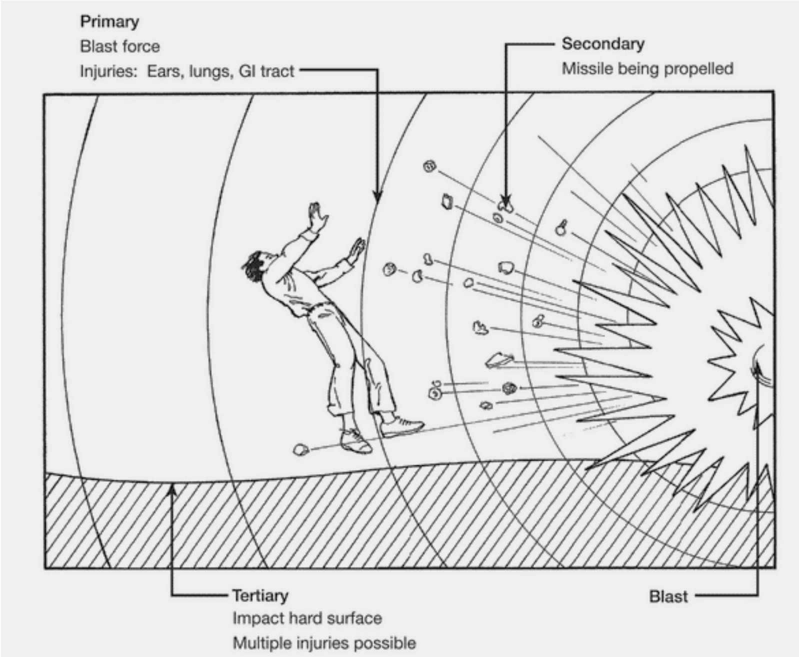


Figure 2.5: Primary, secondary and tertiary blast effects. Adapted from (Newberry L 2003).

2.2.4 Primary Blast Injury

Primary blast injury occurs as a result of the shock wave and peak overpressure transmitted from an explosion through body tissues. The effects of the shock wave on its surroundings depend on the interface of the blast with the body region, and the characteristics of that body region. In particular, in contact between tissues of differing states (air-fluid, solid-fluid, air-solid) the blast wave is magnified by differential acceleration of the pressure wave occurring within tissues of differing characteristics (Ritenour and Baskin 2008). Blast overpressure particularly affects the air filled structures within the body such as the lungs, ear and hollow abdominal organs. However, some theories of primary blast biomechanics also conclude that primary blast injury can affect all body tissues, regardless of the state of matter (Hull and Cooper 1996). Shearing and compression forces as the result of blast cause many different injury types, potentially affecting all body regions. The closer the individual to the blast wave, the more severe the effects from primary blast.

2.2.5 Secondary Blast Injury

Secondary blast injury concerns fragments that have been propelled due to explosive forces as a consequence of the primary blast wave and resultant blast wind (Hill 1979). The constituents of this solid matter can be components of the outer casing of the explosive device, solid fragments embedded within a device designed specifically to inflict injury (both termed primary fragments), and elements of the surrounding environment such as dust, grit and sand (secondary fragments). Secondary fragments occur more frequently, and to a greater extent, in explosive devices that are buried beneath the ground (Zorpette 2008). In addition, items of clothing or solid implements on and around an injured person can become secondary projectiles, as can biological contaminants from suicide bombers or nearby victims such as bone or tissue fragments, which can be an additional biological insult (Patel et al. 2012). Secondary blast particles travel at a high velocity and have the potential to pierce protective outer equipment and clothing, and can be particularly destructive. They are also a constant source of contamination and later infection to a patient, and can cause infective complications both in the initial phases, and later in the treatment and rehabilitation pathway, potentially complicating recovery (Bowyer 2006). Secondary blast injury affects all body regions, regardless of composition, however, the composition of the structure penetrated will resist or limit the penetration of fragments according to its mechanical properties (Covey and Ficke 2016; Nyström and Gylltoft 2009).

2.2.6 Tertiary Blast Injury

Tertiary blast injury occurs as solid structures, like vehicles or buildings, impact a casualty, or a casualty themselves if flung against a solid structure due to the blast wave or wind. This results in a blunt impact that can affect any body region and lead to fracture, physical trauma, and physiological effects due to muscle crush and rhabdomyolysis. Flail of the extremities can also be classed as a tertiary blast effect, as this involves the sudden displacement of a body region. This has the potential to cause shearing of the junctional regions of the extremity and torso, although it is likely that an initial axial load is required to cause fracture, with a subsequent flail (Hull and Cooper 1996).

2.2.7 Quaternary Blast Injury

Miscellaneous injury types related to blast are included in this subgroup, which includes thermal injury to tissues, subsequent inhalation of harmful gases, and asphyxia. Fires following explosive events are surprisingly unusual, due to the available oxygen required for ignition and maintenance being used up in the initial explosive process, however, secondary fires can, and do, occur (DePalma et al. 2005). Burns in blast injury can be one of two types: flash burns at the time of explosion, and those caused by any secondary fires. The former are more superficial, and occur, for example, in exposed tissues of the face and hands, with clothing somewhat protective. Secondary fires cause more severe and deeper burns (Turégano-Fuentes et al. 2008), this is due to their sustained nature, and additional injuries often mean the individual is unable to halt the burning process.

Some authors consider quinary blast injury as an additional subset of blast effects that includes introduction of additional injurious contaminants, unrelated to the actual physical mechanism occurring in the explosion. This can include subsequent infection with bacteria or viruses introduced from the surrounding environment at the time of blast, a systemic inflammatory response characteristic of blast injury (Kluger et al. 2007), or as a purposeful contaminant impregnated into the device by the creator of the explosive in order to maximise harmful effects. Radiation is also a potential contaminant within explosions, and one which may lead to harmful effects long after the explosive event (Zimmerman and Loeb 2004). It is possible that infection can be transmitted between individuals from biological tissues, and blood borne pathogens released on tissue trauma to nearby individuals. This can indeed also be purposeful (Frickmann et al. 2013), and there has been some call to evaluate whether post exposure prophylaxis to blood borne pathogens is appropriate in blast injuries (Subbarao et al. 2007).

2.2.8 Combined Effects of Blast Injury

These injury classifications are useful in compartmentalising the effects of blast, which can be difficult to understand when considered as a combined event. However, in reality, most injuries are caused by a combination of all categories of blast, and the effects of each must be considered when analysing injury patterns (Brismar and

Bergenwald 1982). It is also considered anecdotally, as a restrictive method to compartmentalise blast injury, as some injury types do not fit clearly into these defined categories. For example, behind armour blunt trauma (BABT) is the phenomenon occurring when the effects of the explosion lead to the deformation of body armour plating and inflict injury (Cannon 2001; Lidén et al. 1988). This is a blunt impact, and could be deemed a secondary blast effect as an item is impacting an individual, however, a large blunt item causes very different effects to smaller fragments and debris, classic of a secondary blast injury. Therefore, in such different clinical outcomes, it may be inappropriate to group these two scenarios together. In addition, underbody blast (UBB) is a term which describes the floor deformation that occurs when an IED detonates beneath a vehicle, and injures occupants within. This is also a blunt impact, and it may be inappropriate to consider this injury mechanism with finer fragment secondary injury, as in BABT. Certainly, the mitigation of injury is likely to be different in these two mechanisms. Therefore, although these descriptions are helpful in understanding blast injury effects, it is important to remain accommodating to new ways of thinking with regards to blast injury mechanisms.

The surrounding environment is also an important consideration to understand, as it has a significant influence on the effects of blast, and the resulting injuries seen.

2.3 Differences in Explosive Effects with Environment

It has been well recognised throughout the literature that the environment surrounding explosive events influences the character of the blast (Horrocks 2001). The effects are different depending on whether the blast occurs in an open space or confined environment, and differences have also been observed in explosions occurring underwater.

2.3.1 Open Spaces

Blasts occurring in open spaces with little infrastructure or terrain to interfere with the process of the blast follow a fairly predictable pattern of positive and negative pressure changes as per the Friedlander waveform (Yeh and Schecter 2012) (Figure 2.4).

Individuals subjected to these ‘open field’ types of blast wave are subjected to an unimpeded primary blast wave, the effects of which dissipate fairly rapidly with proximity from the device (Arnold et al. 2004). Therefore, depending on the size of the blast wave, personnel within fairly close proximity to the blast experience the classic disruption at air fluid interfaces within the body (Nelson et al. 2006). Examples of these regions include bowel, lung and tympanic membrane (Mayorga 1997). The main source of injury in open blast events is derived from secondary injury, with fragmentation travelling at supersonic velocities, which can be highly destructive and disrupting tissues of all types (Christensen et al. 2012). Tertiary injury is less prolific in these incidents, as there are few artefacts to cause injury, although the affect from floor deformation depending on the constituents may lead to tertiary axial loading via the lower limb (Ngo, Mendis, and Ramsay 2007). There is also mounting evidence that the primary blast wave is responsible for many of the skeletal injuries that may occur with a non-impeded blast wave, however, this is still debated in the literature (Guy, Glover, and Cripps 2000). Burns (quaternary) injury can also occur in blast in open spaces as flash or secondary burns.

2.3.2 Confined Spaces

In confined spaces and semi-confined spaces, the primary blast effects on the human body are much more severe (Leibovici et al. 1996; Rezaei, Salimi Jazi, and Karami 2014). This is due to the confined spaces causing the initial shock wave impulse from the blast wave to rebound from buildings and infrastructure which therefore extends for a longer duration, maximising injury potential from the blast overpressure (Chaloner 2005). This leads to previously described characteristic injury patterns seen due to primary blast wave effects (Katz et al. 1989). Casualties may be relatively well protected from secondary blast injury fragmentation due to the shielding effects of vehicles or buildings if they remain intact, however, if breached, then secondary blast injury can be seen. The risk of tertiary injury in explosions in confined spaces is high, due to deformation of the surrounding environment causing relative displacement of structure and occupant. This includes impact due to deformation of vehicle floors (UBB) (Ramasamy, Hill, Phillip, et al. 2011), or the casualty being flung against buildings, or against the inside of vehicles, particularly the vehicle roof, causing head injury (Sponheim et al. 2011). Confined spaces include vehicles, examples of which could be road vehicles, trains, or underground metro lines. In the latter, the blast wave is maximised further, and can be considered as an 'ultra-confined' space, where the effects from the primary blast wave will be further potentiated. There is often a high concentration of people in a small space utilising these transport methods, so a high number of casualties can result from these scenarios (Cooper et al. 1983; Kluger, Kashuk, and Mayo 2004). Concerning blast occurring in and around enclosed spaces there is a differentiation to be made between the blast occurring *within* the enclosed space, where injury due to primary blast overpressure is much more prolific, and blast occurring *outside* the enclosed space. Casualties may be relatively well protected from an outside blast due to the infrastructure surrounding them, unless this infrastructure becomes breached by the blast. The relative protection from the infrastructure can be countered but the resulting tertiary blast injury that can leads to blunt injuries.

2.3.3 Under Water

Immersion in water is another environment in which blast effects can be further intensified, and therefore tend to be more severe. These effects were initially noted in sheep, dogs and monkeys in which blast lung and bowel perforations were recorded when subjects were immersed in water (Richmond, Yelverton, and Fletcher 1973). This has been tested experimentally by a later study performed on dogs, submerging their abdominal regions to underwater blast. This led to intra-abdominal injuries such as bowel perforations, which were not present in subjects out of the water (Russ Z 1991). This potentiated effect is due to the higher mass of water compared with air, and relative incompressibility meaning that the blast wave transmits force to a greater range and magnitude underwater (Stuhmiller et al. 1991).

Understanding blast in terms of primary through to quaternary injuries, and the differences in effects due to the environment surrounding the casualty and the explosion are paramount to understanding blast injuries. When these influencing factors are understood, instead of a seemingly chaotic event, blast effects to the human body can cause predictable injury patterns.

2.4 Blast Injury in Warfare: Patterns of Injury

The use of explosives as a weapon can affect all body regions, and the consequences vary depending on both the nature of the explosive and the environment in which the explosion occurs. Conflicts do, however, appear to be fairly consistent in the spread of injuries per body region since the time when explosives were used regularly in warfare, and where reliable data exists (Beebe and DeBakey 1952; Belmont, Schoenfeld, and Goodman 2010; Hardaway 1978; Owens et al. 2008b; Reister 1973) (Figure 2.6), with extremity injury being the most prevalent.

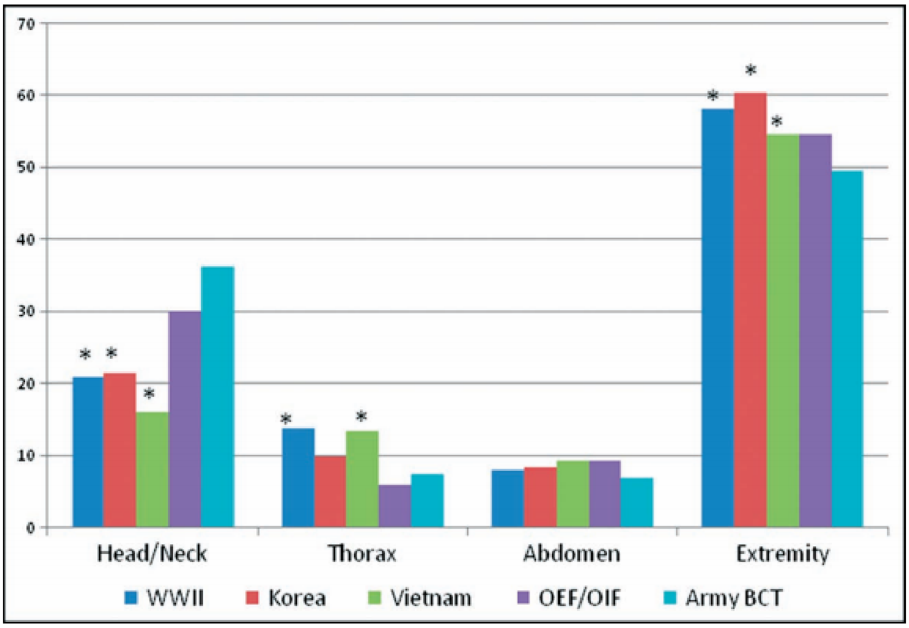
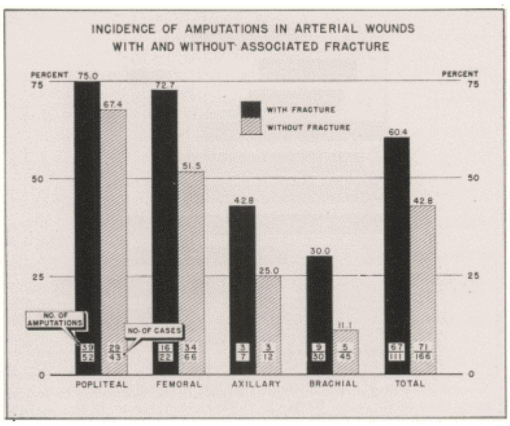


Figure 2.6: Major conflicts of the 20th and 21st centuries, and the distribution of body region injuries as a percent of all injury regions within that conflict (OIF: Operation Iraqi Freedom/ Operation Enduring Freedom, Army BCT: Army Brigade Combat Team) Reprinted with permission from the Southern Orthopaedic Association. Belmont PJ, Schoenfeld AJ, Goodman G. Epidemiology of combat wounds in Operation Iraqi Freedom and Operation Enduring Freedom: orthopaedic burden of disease. J Surg Ortho Adv. 2010;19(1):2-7.

2.4.1 Extremity Injury in Blast

Injuries to the extremities have been the most common body regions injured in war casualties throughout recorded historical accounts (Debakey and Simeone 1946a; Owens et al. 2008b; Woodhall and Beebe 1956). Incidences of extremity wounding in war casualties can reach up to 90 per cent of all injuries (Holcomb, Mcmullin, et al. 2007), and this is for a variety of reasons depending on the nature of conflict and the type of weapons used. The torso and head are relatively well protected with helmets and plating, with armour of various types (Breeze, Horsfall, and Hepper 2010). These areas require relatively little mobility, and can therefore afford greater protection, where the expense of agility is often an issue with greater body region coverage (Larsen, Netto, and Aisbett 2011) (Dempsey, Handcock, and Rehrer 2013). The upper extremities are required to operate weapons, and the lower extremities for mobilisation, and therefore can be more exposed and liable to injury. Even modern body armour materials such as Kevlar^{TM} can carry a significant weight, and it may not be appropriate in all circumstances to carry this weight on all body surfaces due to inability to carry out required functions, in addition to the potential for overheating (Horsfall, Champion, and Watson 2005). With the limbs being remote from the relative protection of the bulk of the torso, they therefore can be vulnerable (Greer, Miklos-Essenberg, and Harrison-Weaver 2006). An additional factor which emphasises the vulnerability of the extremities, is that they, particularly the lower limbs, are often a target in warfare. Extremity injuries can render the victim immobilised, with less fatal wounds, but the ability to be captured and retained as a prisoner of war. Throughout history, great swathes of prisoners have become bargaining tools in political negotiations in some conflicts after tactical injury infliction rather than an enemy intending to kill (Franke 1996).

Upper and lower extremity wounding still accounts for a significant proportion of war injuries in the most recent conflicts (Belmont et al. 2012; Owens et al. 2008b). Lower extremity injuries in particular, akin to the experience of historical wartime data, makes up a considerable portion of extremity wounds (Clouse et al. 2006; Lin et al. 2004), and are responsible for a high number of fatalities (James A G Singleton et al. 2013)(Figure 2.7).



(a)

Anatomic distribution of extremity vascular injuries

Anatomic location	Artery	Injuries (n = 134)	%
Upper extremity		(40)	(29.9)
	Axillary	4	3.0
	Brachial	25	18.7
	Radial/Ulnar	11	8.2
Lower extremity		(94)	(70.1)
	Iliofemoral	9	6.7
	SFA	29	21.6
	PFA	6	4.5
	Popliteal	29	21.6
	Tibial	21	15.7

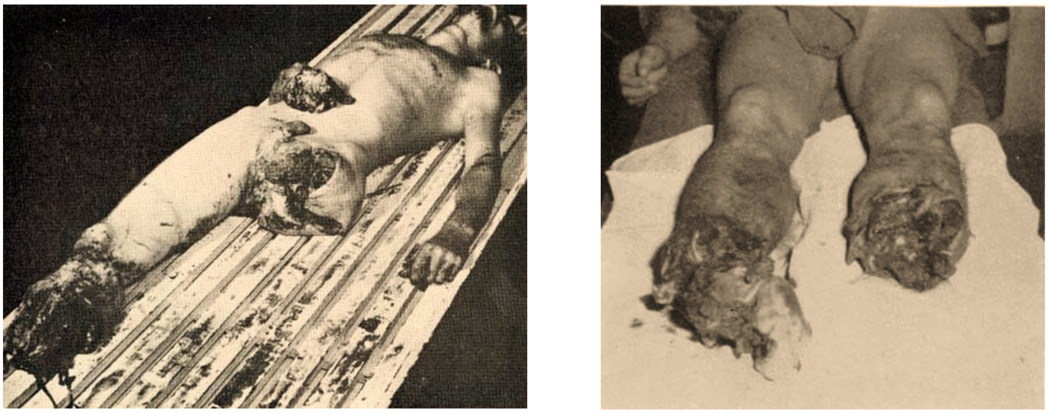
SFA, Superficial femoral artery; *PFA*, Profunda femoral artery.

(b)

Figure 2.7:(a) Upper versus lower extremity arterial injuries in World War II: adapted from (Debakey and Simeone 1946b)(b) compared with extremity vascular injuries in the recent conflicts in Iraq. Reproduced with permission (Peck et al. 2007).

2.4.2 Lower Extremity Wounding

The main factor contributing to this continued high incidence of lower extremity injuries in recent conflicts is the widespread use of IEDs, in particular the ground level placement of these devices, and the relative lack of protection to the lower extremities, particularly in the earlier stages of the conflict. These explosive injuries to the extremities can be very destructive, (Bumbasirević et al. 2006), and even complete separation of the limb from the torso, termed ‘traumatic amputation’ (TA) can occur. TA of the extremities has been a recognised pattern of injury in the more recent conflicts, widely publicised in the literature and the press, as a significant and emotive result of the recent wars (The Guardian 2012). Soldiers are generally a young and motivated patient cohort, and the advances in rehabilitation and prosthetic devices of our time has seen amputees retain a significantly better quality of life than in previous conflicts, and even go on to represent nationally and internationally in sporting events, and at a high level in Paralympic competitions (Burkett 2010), attracting significant publicity. However, the widespread publicity of the recent group of traumatic amputees does not mean that this injury pattern is a new phenomenon. TA of the extremities has occurred throughout the majority of conflicts in which explosives have been used as a weapon (Mabry 2006)(Figure 2.8). The difference between these historical patients and the casualties of the recent conflicts is that many of the patients of recent times *survived* these similar injuries. This is due to many contributing factors, most prominently: early cessation of major haemorrhage, and early blood volume replacement, with prompt evacuation to specialist teams with appropriate resources.



(a) **(b)**

Figure 2.8: (a) Double amputation with high left transfemoral amputation with abdominal wounds and (b) double below knee extremity amputation in World War II. Adapted from (Oughterson et al. 1962)

2.4.3 Control of Major Haemorrhage in the Lower Extremity

Early control of major haemorrhage is one of the main determinants of survival in battle wounds, with studies as early as the 1950s demonstrating that the volume of blood loss is the most significant indicator of mortality in combat wounds (Beecher 1952). Haemorrhage prevention is key to surviving blast injuries, regardless of which body region is injured, and blast events have the potential to injure multiple body systems. Throughout the conflict in Afghanistan, rapid evacuation, care at the point of wounding, and the quality of medical treatment lead to many patients who previously were presenting with injuries deemed 'unsurvivable' surviving their injuries. This achievement is a huge credit to the medical teams and logisticians. In the absence of injury to the head, thorax and vital organs, fatalities in lower extremity wounding are secondary to uncontrolled major haemorrhage (Carey 1996) (Hodgetts et al. 2006).

Control of severe lower extremity injury and TA is clearly an area of focus, as there is a potential opportunity to further increase survival rates in these types of injury. Previous work on lower extremity amputation demonstrates that mortality secondary to TA is dependent on the level of amputation with more proximal amputations being associated with a higher mortality (J J Morrison et al. 2012). This is related to the catastrophic haemorrhage, with exsanguination occurring rapidly. Where higher pressure arterial structures are involved, for example the major limb arteries, blood volume is lost more rapidly, and it is more difficult to achieve adequate compression to control bleeding with first-aid measures. The Combat Application Tourniquet (CAT) (CAT Resources, LLC, Rock Hill, SC, USA) is a mechanism used to achieve this required pressure, but with more proximal amputations at the thigh and hip it is difficult to apply the CAT, which may be why these peripheral-extremity and junctional injuries account for over 30% of 'potentially survivable' deaths on the battlefield (Eastridge et al. 2012a). In addition, the more proximal the amputation, the higher the likelihood of sustaining associated injuries to the pelvis, perineum, and abdomen, which is likely to contribute to fatality (Eastridge et al. 2012a; Penn-Barwell et al. 2014). Severe pelvic and perineal injury in particular was a challenge to the medical teams in Afghanistan (Mossadegh et al. 2012a) with this complex injury pattern requiring significant multidisciplinary efforts to ensure survival and optimal outcomes (Eastridge et al. 2012a; Ramasamy et al. 2012b).

Despite the overall injury burden inflicted by these lower extremity blast injuries, survivability did increase throughout the conflict (Penn-Barwell et al. 2015). It is felt that the care provided during the recent conflicts could be considered superior to the best civilian trauma treatment facilities, and could not be bettered in terms of treatment post injury (Blackbourne et al. 2012; Macdonald 2010). Nonetheless, fatalities still did occur, the majority of which were 'killed-in-action (KIA)' or 'unsurivable.' However, the cohort of casualties with potentially survivable injuries, consisting of up to 25% of those who died on the battlefield prior to reaching a medical facility, (Holcomb, McMullin, et al. 2007; Mohan, Milbrandt, and Alarcon 2008) can serve as a population of casualties where improvements in injury prevention or mitigation targeted at injury patterns sustained by this cohort may result in further lives saved.

The increase in survival in lower extremity wounding seen in recent times has enabled a richer understanding of differing injury patterns in different environments, and what truly constitutes an unsurvivable injury. With the ever increasing survivability of blast injury due to increasing knowledge, logistics (prompt evacuation and allocation of resources) and management improvements, the benchmark for higher and higher standards in outcomes is ever shifting. Ever improving standards of care, and employment of clinical governance methods have meant that excellence must be strived for in combat casualty care, up to and often achieving standards well above that of care in civilian units in the UK, and this was widely reported to be the case in the two most recent major conflicts.

2.5 Blast Injury in Iraq and Afghanistan: Explosive Types and Injury Patterns

The recent conflicts in both Iraq and Afghanistan mirrored injury patterns seen in previous conflicts in terms of likely body regions injured in explosive events. Such explosive events have made up the majority of injury mechanisms in the recent conflicts in Iraq and Afghanistan (Icasualties.org/OEF/Fatalities.aspx 2017). There were differences however, in the types of explosives seen in the two conflicts. The dominant explosive type in Iraq was the Explosively Formed Projectile (EFP). These were first developed in WWII, and comprise an energised, shaped fragment capable of piercing armour, vehicles and infrastructure (Katz et al. 1989). Afghanistan instead saw a higher prevalence of the IED, buried in the majority of cases, but in occasional cases also suspended from the ground to cause more severe injuries to vital body regions such as the head and thorax and result in fatalities. There were found to be differences in injury patterns in patients on foot at the time of injury (dismounted), versus in vehicle (mounted); these are discussed in the following sections.

2.5.1 Differences in Injury Patterns Afghanistan: Mounted versus Dismounted

Analyses of the type of environment and potential differences in injury patterns sustained in war has not been carried out in previous conflicts. It is only in the most recent conflicts in Afghanistan that links have been made between injury patterns and whether casualties are dismounted or mounted (sustaining UBB) at the time of injury. This information is crucial to injury prediction, and when considering prevention of injury. Singleton et al (2013) has demonstrated key differences in these environments in his mortality review: patients in vehicle at the time of injury are most likely to die from a head injury, and to a lesser extent, intra-cavity haemorrhage. Those out of vehicle at the time of injury are more likely to die from haemorrhage, with extremity regions the most affected, followed by more proximal, junctional regions (Figure 2.9).

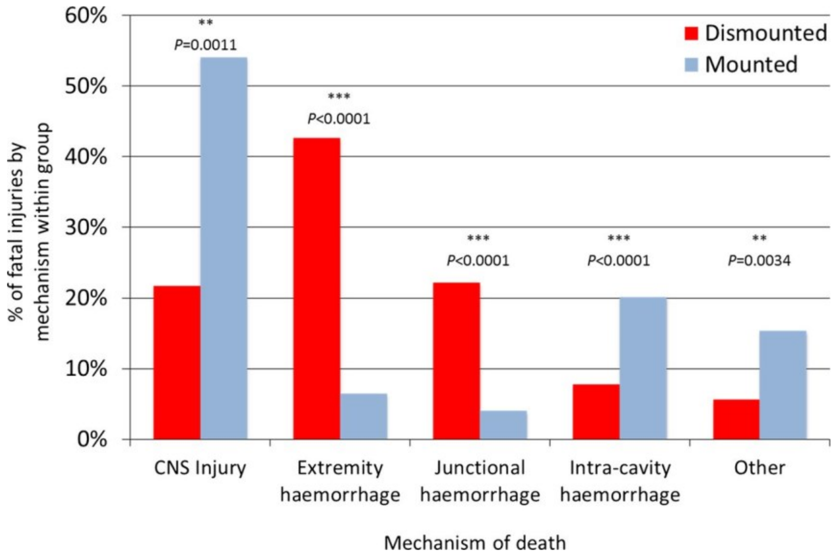
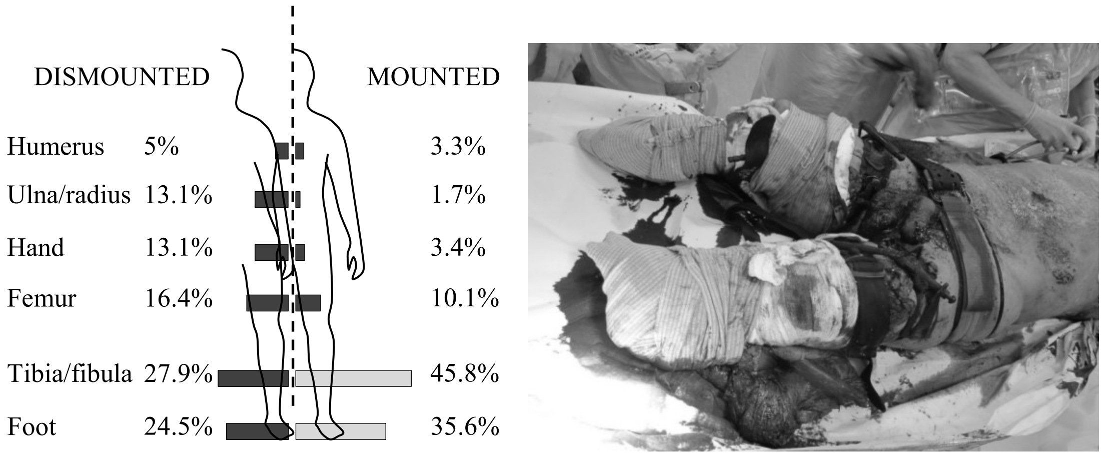


Figure 2.9: Mechanism of Death, mounted versus dismounted. P. values correspond to statistically significant differences in incidence between injury patterns and mounted and dismounted environment at the time of injury. (CNS: Central Nervous System). Reproduced with permission (James A G Singleton et al. 2013).

According to this analysis, as a total of all patients, haemorrhage was a key cause of fatality. The extremities and junctional areas have been identified in this study as an important area of focus. An additional analysis of extremity injuries by Ramasamy et al. (2013) corresponds to the findings in previous conflicts that the lower extremity is responsible for the vast proportion of all extremity wounds, and remains a region of interest in increasing survival rates with this injury pattern (Figure 2.10a). TA of the lower extremity has been proven to be highly contributory to poor outcomes in lower extremity injury due to injury severity and overall injury burden (Zouris, Wade, and Magno 2008), and prior to the recent conflicts, was mostly a feature of fatal wounding (Hull 1992a) (Figure 2.10b). TA was increasingly observed in survivors of blast injury in the recent conflicts, however, it was also a substantial cause of fatality (J. J. Morrison et al. 2012). The fact that survival is possible leads to further questions as to the exact cause of fatality in lower extremity wounding, and what can be done to raise survival rates even higher in future conflicts.



(a) (b)

Figure 2.10: (a) The spread of injuries by body region in mounted and dismounted soldiers Reproduced with permission (Ramasamy et al. 2013) (b) Typical effects of lower extremity blast wounding: bilateral lower limb amputation, perineal and pelvic injuries.

2.6 Conclusion

War injuries from explosive devices are complex and diverse, with a high morbidity and mortality. Increasing survivors in explosive events involves a thorough understanding of injury mechanisms, as presented in this chapter, so preventative measures can be speculated and further tested. Focussing on the lower extremity wounding, as the most often affected body region in blast, with a focus on control of major haemorrhage, potentially has the greatest capacity to increase future survivors. Chapter 3 presents an analysis of a large dataset of lower extremity blast injuries from the conflict in Afghanistan, with a particular focus on TA. With this information, an analysis of the cause of fatality in these patients is presented, with a following method on how to further investigate lower extremity blast injury.

CHAPTER 3

AN ANALYSIS OF LOWER EXTREMITY BLAST INJURIES FROM IRAQ AND AFGHANISTAN

Chapter 2 detailed the evolution of war and weapons, and how and why explosives have become the major mechanism of wounding of our recent times. The review of the blast process outlined the characteristics of blast injury, and how these exert their effects on human tissues. The mortality reviews that have taken place after the close of the recent conflicts have attributed lower extremity wounding to be the body region most likely to sustain injury in explosive events. Traumatic amputation is an important focus, where life threatening haemorrhage can and does occur. Therefore, control of major lower extremity haemorrhage is key to survival, and a major focus for improvements. Detail on specific injury patterns, particularly fatal wounding mechanisms in the lower extremity are however, not yet well known, and must be understood in order to develop improvement strategies. This chapter therefore presents a large dataset on the lower extremity wounding throughout the conflict in Iraq and Afghanistan, between 2003-2014.

3.1 Introduction

A review of the literature in the previous chapter highlighted the lower extremity as not only the most common body region affected by explosive injury, but also that a high incidence of potentially preventable deaths occur in this patient group. This chapter presents the largest cohort of UK casualties to date with lower extremity wounding from the most recent conflicts. It is analysis of injury data that is important to understanding the effects of weapon types on the human body, and without this, clinicians would be unable to audit medical standards and focus on improving outcomes. It is crucial that every injury and life lost in major conflict is not in vain, and allows lessons to be learned to drive standards in combat casualty management. In addition, such information is crucial to inform decision making and intelligent risk analysis for commanders on deployment.

It is not enough to do our best. Sometimes we have to do what is required

Sir Winston Churchill.

3.1.1 Data Collection and Clinical Governance in Conflict

Data collection in wartime has always been challenging. In the austere environment casualties often present en masse, and can overwhelm medical facilities. Record keeping has historically been poor, particularly before computerised records were possible. The importance of keeping accurate records however, cannot be overstated for the following reasons. Firstly, these records document individual patient details, treatment given, and investigation results in order to ensure the patient's management pathway is organised and well communicated among, potentially, many different medical teams and across many different specialties. Secondly, it enables continual analysis of casualty data. The analyses which took place throughout the most recent conflicts were paramount to documenting injuries, survival data, managing ongoing care, and predicting presenting injury patterns and subsequent healthcare requirements (Eastridge et al. 2009). This information is the only way that outcomes can be effectively analysed and disseminated worldwide to establish the level and quality of treatment, and methods in which improvement is required. It is well documented that war propels progress in the management of major trauma (Aldea, Aldea, and Shaw 1987; Bellamy, Maningas, and Vayer 1986; Eastridge et al. 2006), and proper record keeping, data analysis, and subsequent improvement strategies are key for continuing to advance trauma care at the time of the conflicts and for the future (Eastridge et al. 2011). In addition to improving outcomes, this emphasis on data collection allows the development of governance methods, whereby not only is excellence strived for, but also robust accountability and transparency can be ensured (Smith et al. 2007a).

3.1.2 Data Collection and Clinical Governance in the Recent Conflicts

In the recent conflicts in Iraq and Afghanistan, the Joint Theatre Clinical Case Conference (JTCCC) was a system implemented to enable a team of subject matter experts to support decision making in clinical care, and ensure care met best practice guidelines (Willdridge et al. 2010). This was only possible with accurate and succinct data collection methods. In addition to analysis of wounded casualties and discussion on appropriate management, the introduction of compulsory computerised topography (CT) scanning was routinely employed in November 2007 for all casualties who were killed in action, or died of wounds (J. Singleton et al. 2013). The information gained from the introduction of this was crucial to understanding injury patterns and further informing mitigation strategies in many specialties (Breeze et al. 2015). In addition to the JTCCC, a detailed review of each fatality also occurred. In these reviews, an assessment of the potential survivability of injuries took place, and interventions were scored according to fixed performance indicators (Smith et al. 2007b) to assess if fatality could have been avoided on the introduction of changes to casualty management.

The conflicts of Iraq and Afghanistan also saw the introduction, by the UK, of the Joint Theatre Trauma Registry (JTTR). The JTTR is a prospectively collected database held by the Royal College of Defence Medicine (RCDM), in Birmingham and the property of the Ministry of Defence (MOD). It is managed by UK Defence Statistics and follows strict clinical governance guidelines with regards to information storage and confidentiality. It contains details of all UK casualties injured while overseas on operations, and also includes those coalition forces, local nationals and any other patient treated in the UK deployed medical facility. The data include demographics, injuries sustained, interventions, and outcomes - both immediate and late fatalities are included. Information is entered at the time of injury, and updated throughout the patient pathway, including, if applicable, post mortem data. This includes any data from post mortem scanning or formal physical post mortem examination, if a fatality occurs. This implementation of trauma registries, both the JTTR, and the Joint Theatre Trauma System (JTTS), the equivalent to JTTR in the United States defence medical services, have had a profound impact on setting the standard for deployed casualty care. There is also evidence that trauma registries in wartime tangibly improve outcomes by way of implementing performance indicators, and introducing evidence based clinical practice guidelines (Eastridge et al. 2009).

3.2 Aims and Hypothesis

The importance of lower extremity injuries from blast incidents has been recognised, not only the potential gravity and lethality of injuries to this body region, but also the potential for survivability. This analysis was therefore performed in order to:

a. understand the full extent and volume of lower extremity injuries with a complete analysis of lower extremity injuries throughout recent conflicts in Iraq and Afghanistan due to a blast mechanism;
b. analyse the characteristics of fatal lower extremity injuries from blast;
c. analyse areas in which further study is warranted in order to assess interventions required to improve survival in lower extremity injury.

It is likely that fatal blast lower extremity wounding patterns lead to a consistent causative feature of fatal injuries that can be isolated and further examined in order to assess their preventability.

3.3 Methods

Data collection

The JTTR database was used for this analysis. The database was searched to include casualties who had sustained a lower extremity injury from a blast mechanism in the conflicts in Iraq and Afghanistan between March 2003 to the end of the conflicts in August 2014.

Basic patient demographics were obtained including date of injury, age, sex, status (military or civilian) and patient outcomes, as well as injury details as per clinical examination, radiological findings, post mortem reports and injury severity scores, all of which are available within the JTTR if applicable. Within this patient group, data was specifically sought on the presence of traumatic amputation, the level of amputation, and whether it was unilateral or bilateral. The data collected for the analysis is shown below (Table 3.1).

Data Category	Notes
Demographics	
Date of Birth	-
Age at incident	-
Sex	Male/Female
Service	Army, Navy, RAF, Marines, Civilian, Police, Interpreter, Detainee, Contractor
Status	UK Military, Coalition Military, Local Civilian, Coalition, Civilian, Hostile Civilian, Hostile Military, Local Military
Incident Data	-
Case Date	-
Country of Injury	Iraq/Afghanistan
Force Provider	Iraq, Afghanistan, UK, USA, Estonia, Georgia, Denmark, Estonia, Uganda, Egypt
Injury Data	
Severity Abbreviation	Wounded in Action (WIA) DOW (Died of Wounds) Killed in Action (KIA)
Injury Severity Score	-
Glasgow Coma Scale (GCS)	Objective marker of consciousness
Outcome	Survivor/Fatality
Injury 1, 2 and 3 data	Injury codes and scores by Injury Severity, and injury descriptors
Total Injury Number	-
Amputation Detail	Level, unilateral/bilateral
Treatment Data	-
Operations Performed	Description of procedures
Tourniquet Used	-

Table 3.1: Data Fields Collected.

Definitions

The patient outcomes were classified as ‘wounded in action’ (WIA) ‘died of wounds’ (DOW), or ‘killed in action’ (KIA). Those who were WIA sustained wounding but survived their injury, DOW survived to receive initial treatment but subsequently died, and KIA were immediate fatalities that did not survive to receive initial medical treatment. The Glasgow Coma Scale (GCS) was collected for each casualty, as an objective marker of level of consciousness (Jones 1979).

The injury severity scores used in this analysis was the Abbreviated Injury Severity Score (AIS) (Baker et al. 1974)(Table 3.2), to categorise injuries in terms of severity by different body regions. The top injury regions in descending order were ranked by AIS, meaning 'most severe injury.'

AIS Score	Description
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximal (Currently Untreatable)
9	Unknown Injuries

Table 3.2: The Abbreviated Injury Severity Scale (AIS) severity categories.

Permissions and Data Management

Permission to perform this study was applied for, and granted, in October 2014, by RCDM (audit reference number: 48/2014.) Data were anonymised, with all identifiable features removed, and stored in a secure location.

Data Analysis

Data analysis was performed using Excel 2013 and SPSS statistics software (version 23, Microsoft, 2013). The contribution of specific lower extremity injury patterns to fatality was compared and results assessed for statistical significance. Probabilities of fatality with specific wounding patterns were calculated using chi squared, due to the categorical nature of the variables, with the significance set at $p < 0.05$. Logistic regression to isolate the most significant wounding patterns to fatality from a larger group of variables was performed was using STATA software (STATA Version 22). Statistical advice and oversight was provided by Joseph Eliahoo, Senior Statistician, Statistical Advice Service, Imperial College London.

3.4 Results

3.4.1 Lower Extremity Wounding

A total of 3209 casualties sustained injuries to the lower extremity from blast between March 2003 to August 2014. There were 2617 survivors and 593 fatalities (18.5% fatality rate).

Fatalities

Of the fatalities, the highest (most severe) injury by AIS was the lower extremity in 220 (37%), head in 197 (33%), abdomen in 51 (9%), thorax in 49 (8%), upper extremity in 21 (3%), with the remaining 56 (10%) being ‘other categories’ including whole body injuries and burns. This is illustrated in Figure 3.1.

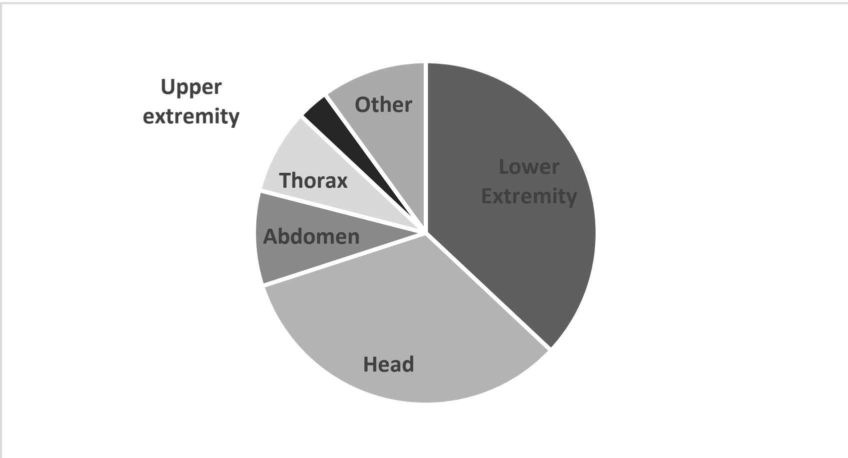


Figure 3.1: Most severe injury regions by AIS in those sustaining lower extremity injuries in fatalities.

Of the fatalities 423 (71%) were KIA, therefore, immediate fatalities prior to medical treatment. Those 29% (n = 170) who DOW survived to reach a treatment facility, but subsequently died of their injuries. A breakdown of injury regions by time of death is presented in the figure below (Figure 3.2).

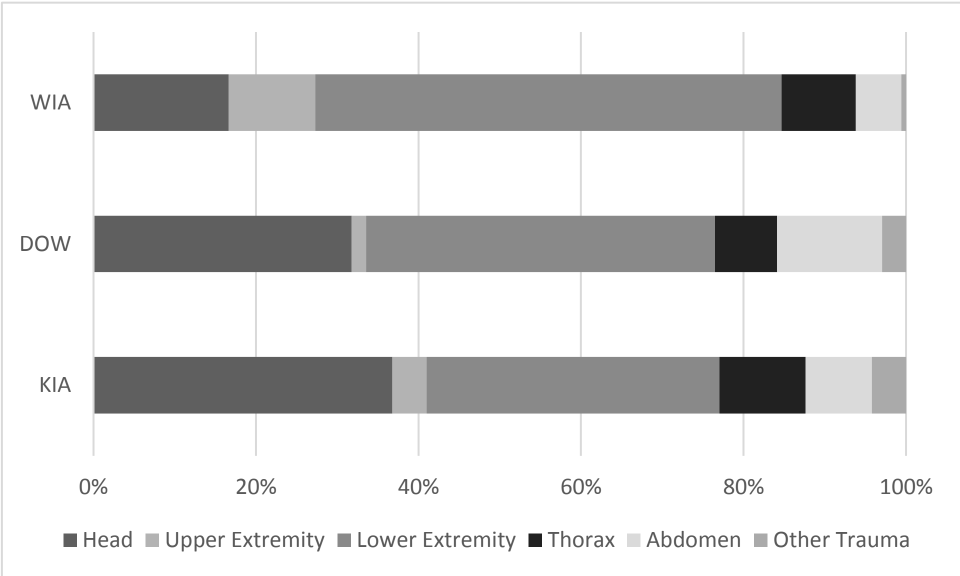


Figure 3.2: Most severe injury regions by AIS in fatalities separated by whether they were WIA, DOW or KIA.

Highest AIS: Head Injury

The data reveal that the incidence of head injury changes depending on outcome, whether a survivor, late fatality, or immediate fatality. Head injury occurs most frequently in immediate fatalities. A total of 149 (38%) of those KIA sustained a head injury as their most severe injury by AIS. Of the 170 casualties who DOW, head injury was also common, with 54 (32%) sustaining a head injury. Head injury is less common in those WIA, contributing to only 17% of these patients. Of those casualties who DOW, 109 (64%) had an initial GCS of 3, with or without head injury, and therefore had a predictably poor outcome (Tien et al. 2006). Head injury is clearly an important injury pattern, as it is responsible for a high number of fatalities in blast injury. However, in terms of *volume* of injury, the lower extremity is more prolific in incidence (Figure 3.1), and has been proven to be a category with potentially preventable fatalities (Eastridge et al. 2012b).

Highest AIS: Lower Extremity Injury

In those immediate fatalities (KIA), 146 (37%) of most severe injuries were to the lower extremity. Lower extremity injury was responsible for the greatest proportion of fatalities in those who DOW (n=43, 73%). The fact that these patients survived the initial insult but died shortly after, suggests that there might have been an opportunity for intervention that was not being utilised to result in survivability. In all fatalities with lower extremity wounding, (both those who DOW and KIA), the majority had sustained a TA; 59 (80.1%) in those who were KIA, 125 (86%) in casualties who DOW, and 185 (84%) of all fatalities (KIA plus DOW). The remaining 16% (n=36) had sustained a major vascular injury within the lower extremity, without TA.

As described in Section 3.1.2, as part of the Defence Medical Services (DMS) Clinical Governance process, all deaths on operations are subject to a detailed case review. Although the specific details of this are out of the scope of this thesis (and subject to publication restriction) it has been confirmed that there were no concerns in the management of lower extremity injuries in fatalities, and categorised these deaths as non-preventable.

3.4.2 Traumatic Amputation

As TA was such an important injury mechanism, increasing the mortality of lower extremity injuries, those TA casualties were reviewed in more detail in the following section.

Patient Demographics

A total of 970 casualties sustaining a total of 1471 lower limb TAs were identified. Of the 970 casualties, there were 674 (69.5%) survivors and 296 fatalities (30.5%). In keeping with the UK Office for National Statistics guidelines, numbers below 5 are not given, to preserve anonymity (Quarterly Afghanistan and Iraq Amputation Statistics 2016), and therefore the data from 2003-5 (12 cases), have been excluded. Between 2006-2014 there were a total of 958 casualties (69.2% fatalities and 30.8% survivors) who sustained lower extremity TAs. The peak incidence of TA was in

2010-2011 and decreased steadily until the end of the conflict in 2014. In general, there was a trend towards increasing survival rates during the conflicts, however, even at the end military activity in 2014 the fatality rate was 23.1% (Table 3.3).

Year	Number of TAs	Survivor	Fatality
2006	12	9 (75%)	3 (25%)
2007	29	17 (58.6%)	12 (41.4%)
2008	64	42(65.6%)	22(34.4%)
2009	115	66(57.4%)	49 (42.6%)
2010	231	140 (60.6%)	91 (39.4%)
2011	249	188 (75.5%)	61 (24.5%)
2012	160	119 (74.4%)	41 (25.6%)
2013	72	62 (86.1%)	10 (13.9%)
2014	26	20 (76.9%)	6 (23.1%)
Total	295	663 (69.2%)	295 (30.8%)

Table 3.3: Traumatic amputations (TAs) by year; survivors and fatalities.

Area of Most Severe Wounding by Body Region

Table 3.2 illustrates that of all the main body regions injured in the TA cohort (scored by the AIS), the lower extremity was responsible for the greatest incidence and highest number of deaths compared with these other body regions (Table 3.4).

Body Region	Number	Survivors (%)	Fatalities (%)
Lower Extremity	817	603 (73.8%)	214 (26.2%)
Head and Neck	70	14 (20%)	56 (80%)
Thorax	19	13 (68.4%)	6 (31.6%)
Abdomen	11	0 (0%)	11 (100%)
Other*	11	3 (27.3%)	8 (72.7%)
Total	958	663 (69.2%)	295 (30.8%)
*Burns, total body disruption, drowning			

Table 3.4: Main injury by AIS of those with TA.

Single versus Double Amputation

The incidence of single versus double amputation varied throughout the conflict, with a higher proportion of double amputations during the peak of activity in 2010-2011, and single at the start and close of the conflict. (Figure 3.3). Double amputation was associated with higher mortality (35.9%) compared with single amputations (25.5%: p = 0.008).

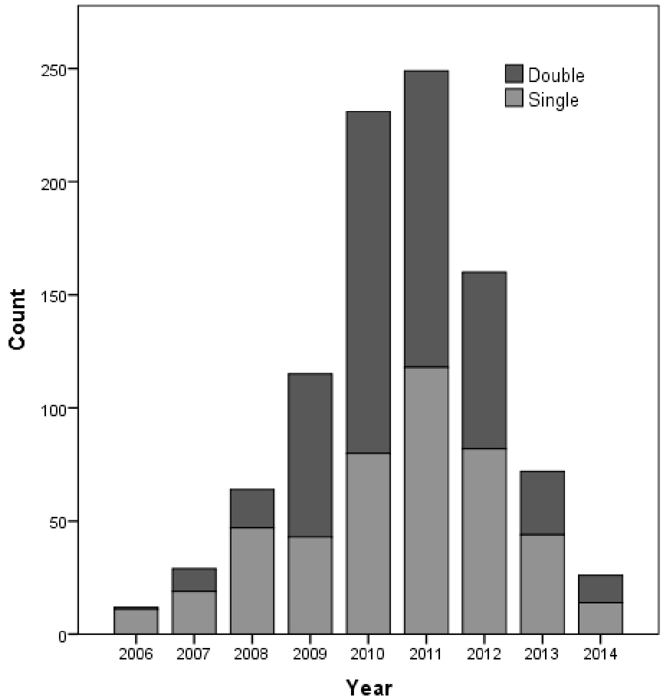


Figure 3.3: The incidence of double and single traumatic amputation by year.

Amputation Levels

The amputation level changed throughout the conflict, with a greater proportion of higher amputations seen at the peak of activity in 2010-2011 (Figure 3.4).

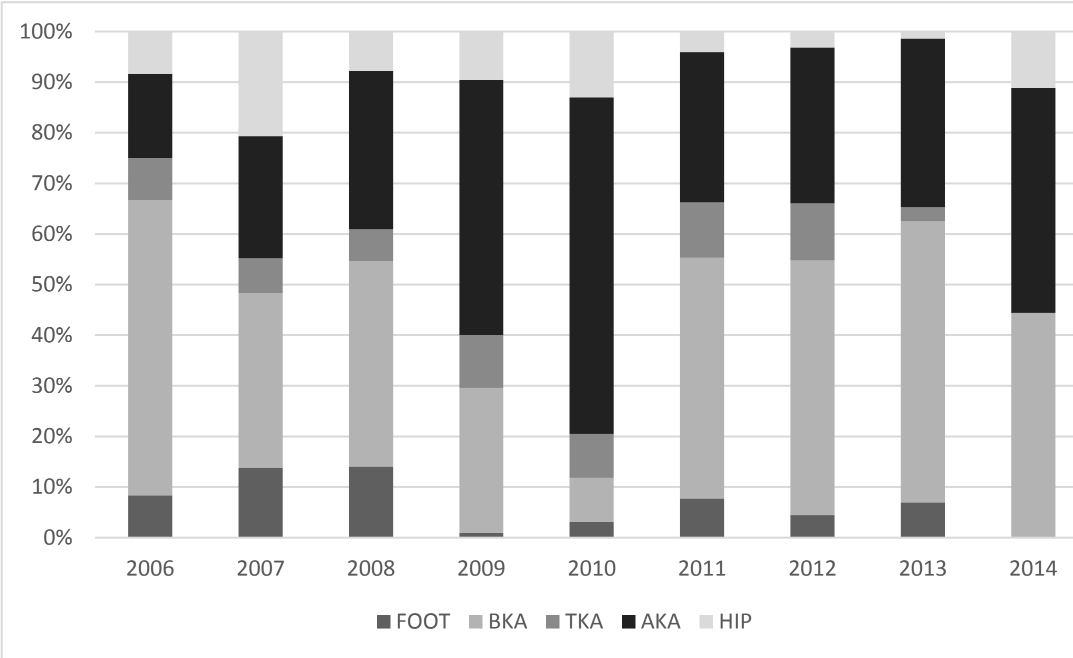


Figure 3.4:Categorised highest amputation levels in lower extremity traumatic amputation casualties, and year the injury occurred. Amputation abbreviations: BKA: Below knee amputation; TKA: Through knee amputation; AKA: Above knee amputation, HIP: TA at hip level

The types of amputation sustained did correlate with fatality, fatality increasing with the higher amputation levels (Figure 3.5), and confirmed in the later logistic regression analysis, OR 0.093 for high amputations compared with OR 1.61 for single or double amputations (Table 3.5). The level was the more significant predictor of fatality rather than whether the amputation was single or double (Table 3.5).

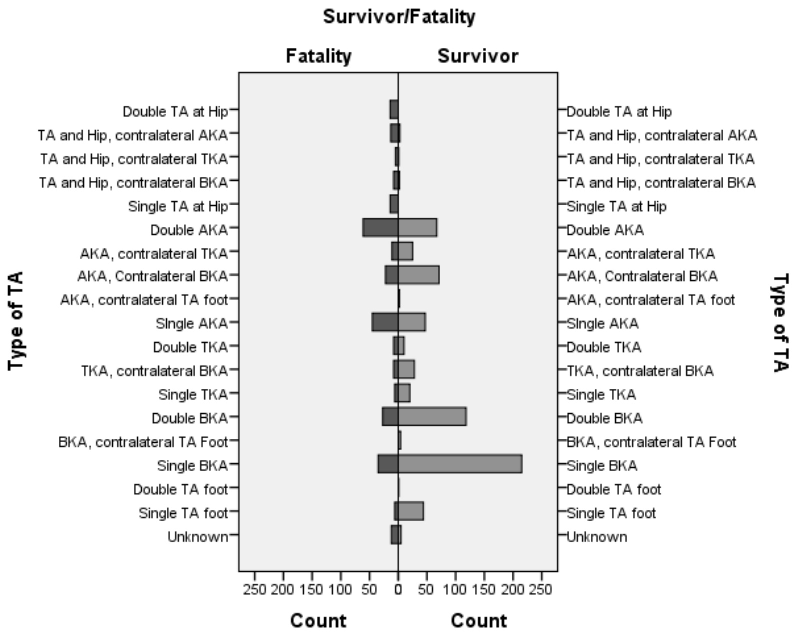


Figure 3.5: Categorised traumatic amputation levels and fatalities versus survivors.

TA at the hip level, either unilateral or bilateral, carries a 100% fatality rate (Figure 3.5), most likely due to a higher burden of injury and a higher change of major vascular injury. TA at the hip, by definition, is a traumatic amputation associated with a concomitant pelvic fracture (PF), which points to the importance of PF in fatal wounding to the lower extremity. Due to the lack of bony fracture in some cases of pelvic injury, (disruption at the joints of the pubic symphyisis (PS) and sacroiliac joints (SIJs)), PF will subsequently be referred to as: pelvic injury (PI).

Associated Pelvic Injury

There were 198 PIs within this dataset, 19% of the TA cohort. Of those casualties with PI, fatality is 60.8% compared with 22.9% without (Chi squared: p = 0.0001). PI is also statistically significantly correlated with the level of TA (p = 0.0001) (Figure 3.6) with higher amputations giving a higher chance of sustaining a PI.

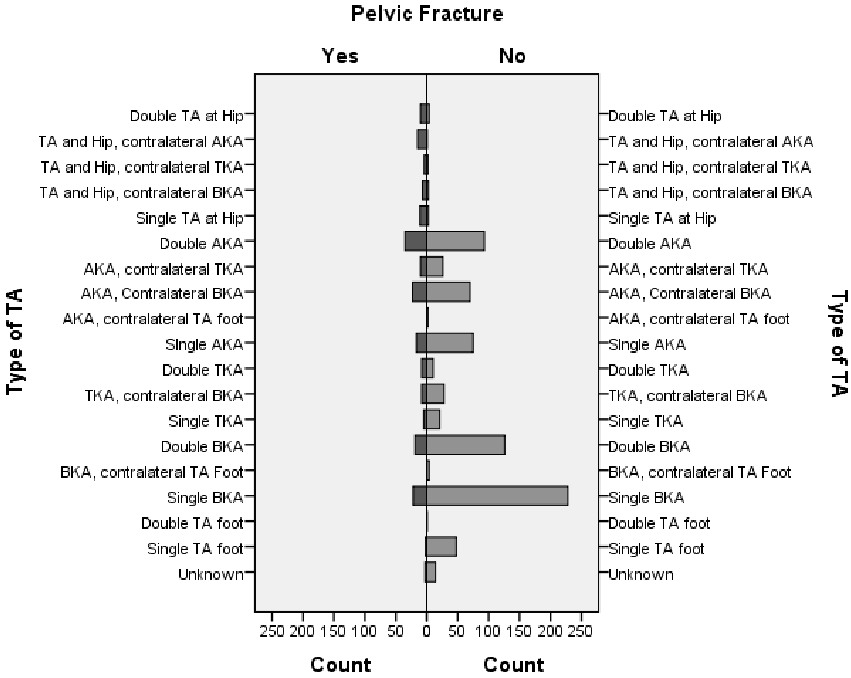


Figure 3.6: Categorised traumatic amputation levels and incidence of pelvic fracture. Abbreviations: TA: traumatic amputation; AKA: Above knee amputation, TKA: through knee amputation, BKA: below knee amputation.

As illustrated in Table 3.4, PI is not isolated to double amputees, however, it occurs significantly more frequently in those with double amputations (p = 0.0001, odds ratio (OR) 3.135, confidence interval (CI) 2.10-4.67). Additional features of fatal injuries included double amputations (p = 0.0001, OR 1.611, CI 1.21-2.12) and amputations higher than the knee level (p = 0.000, OR 0.9, CI.004-0.622) (Table 3.5).

Survival	OR	Std. Err.	z	P>[z]	95%CI	
Pelvic Fracture	3.14	0.64	5.61	0.00	2.10	4.67
Double/Single	1.61	0.23	3.36	0.001	1.22	2.13
TA Level						
Above Knee	0.093	0.043	-5.15	0.00	0.038	0.23
At/Below knee	0.033	0.016	-7.29	0.00	0.013	0.083
Foot	0.017	0.011	-6.14	0.00	0.005	0.062

Table 3.5: Logistic regression with features strongly associated with fatality. OR: Odds Ratio; Std.Err: Standard Error, CI: Confidence Interval, TA: Traumatic Amputation. An underlined result signifies statistical significance.

PI also occurred throughout the types and levels of TA, and could not be isolated to any particular pattern of lower limb outcome (Figure 3.7 and Figure 3.8).

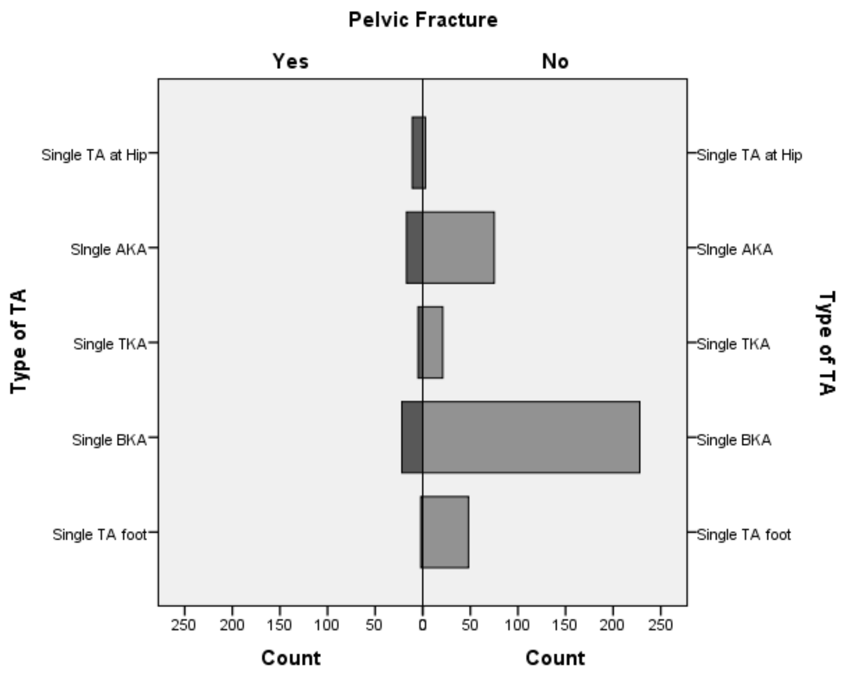


Figure 3.7: The incidence of pelvic fracture and unilateral TA of varying heights.

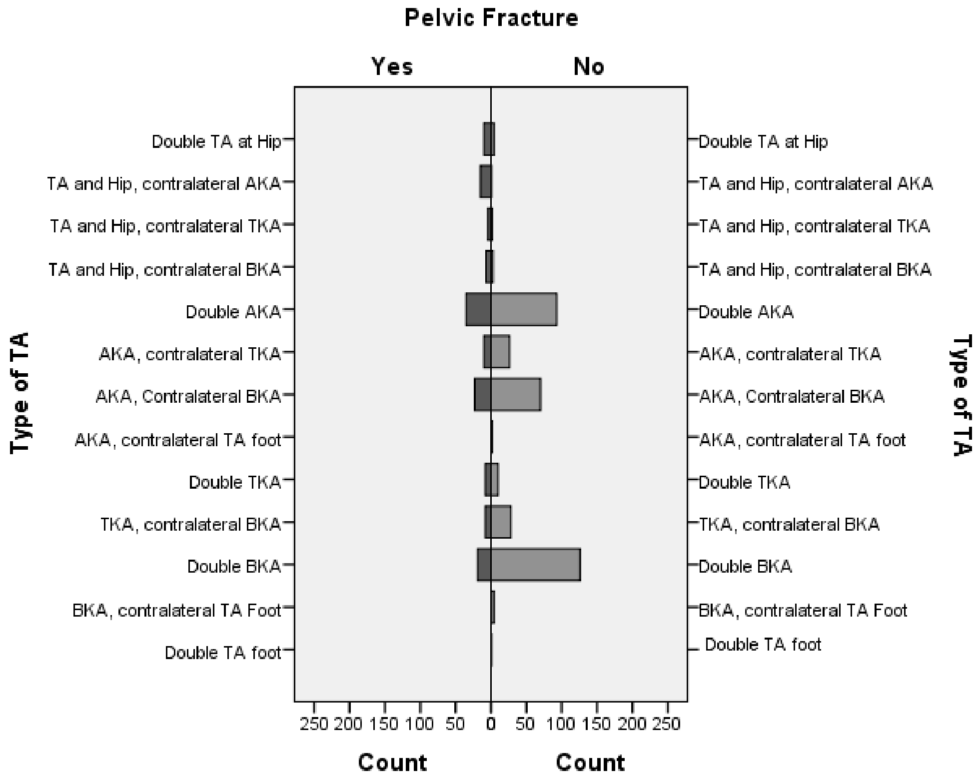


Figure 3.8: The incidence of pelvic fracture and bilateral TA of varying heights.

3.5 Discussion

In previous studies, the lower extremity has been demonstrated to be the most common body region to be injured in explosive incidents in Iraq and Afghanistan, (Edwards et al. 2016), and this correlates with the findings in this analysis. Although many casualties in this dataset died of an additional injury other than to the lower extremity (for example, head or abdominal regions), as with the majority of historical conflicts, lower extremity was still the most common region to prove fatal. As injuries to the extremities can be considered 'potentially preventable' deaths, it is important to understand the exact cause of the fatality in this patient group and therefore to ascertain if the injury was indeed, potentially preventable.

TA is the major contributor to fatality in those with lower extremity injuries, and many of these casualties are KIA: dying before the chance to initiate lifesaving interventions. All deployed soldiers are supplied with Combat Applicator Tourniquets (CATs) which can stop bleeding from amputation sites to injured colleagues as 'buddy aid' or even to their own limbs, however it is clear that even with stringent use of the tourniquet, as was the case in the recent conflicts, fatalities are still occurring and it is important to understand why this is the case. With this understanding, a focus for improving survivability can be created.

Despite the unprecedented level of care provided to casualties of war in the conflict in Afghanistan, fatalities due to traumatic amputations secondary to an explosion were still present at the end of the conflict. This analysis confirms that proximal injuries are associated with many of the deaths seen in the TA cohort. PIs are strongly associated with fatalities, and this is likely to be due to blood loss from major vessels, profound soft tissue injury, and overall injury burden. The presence of PI is not only present in proximal amputations, as they occur within a spectrum of many different injury patterns in the lower limb, including TA at and below the knee. This means it is unlikely to be purely direct impact on the pelvic bones causing fracture. Considering that most of this cohort died of their lower extremity injury, and before medical intervention was possible, a focus on mitigation strategies is likely to yield much higher improvements in outcomes rather than treatment advances. To address mitigation requires a thorough understanding of the mechanism of TA, and concurrent PI, in order to develop methods to prevent or lessen injury burden.

The mechanism of TA is still not fully understood. From experience in Northern Ireland, the mechanism was thought to be secondary to a primary blast injury causing the initial fracture, and subsequent separation of the fractured limb due to the blast wind (Hull 1992b). Experimental techniques were employed in an attempt to reproduce this in an animal model (Hull and Cooper 1996). Interestingly, experience in this era demonstrated predominantly TA secondary to fracture through long bones, and refuted the idea that lower limb flail was the mechanism of injury at this time (Doukas et al. 2013). More recent studies from experience in Iraq and Afghanistan, however, have contradicted this injury pattern and found that through joint amputations have a much higher incidence (J.A.G. Singleton et al. 2013). This has brought into question the injury mechanism suggested previously. To cause separation laterally via ligament and soft tissue disruption implies that flail of the lower limb may indeed be the causative mechanism of TA in this group of casualties. Differences in the patient groups are most likely to be the characteristics of the explosion; car bombs being the principal weapon in Northern Ireland (Doukas et al. 2013) versus the improvised explosive device during recent military activity. Pure axial load via the feet could also be a cause of TA, and could be tested in future work, along with testing a potential flail mechanism in the lower limb.

The link between TA and associated PI in this study and others leads to further consideration of the biomechanics of this blast injury mechanism. It could be that there is a mechanistic link between the two, and so establishing this link is important in designing mitigation strategies. It is not as simple as the higher the amputation, the greater the chance of PI, as the incidence of PI appears in all levels of TA. This suggests that it is not simply direct injury to the pelvic bones with more proximal injuries that causes pelvic fracture; lower amputations at the knee and below can cause disruption of the pelvis. Although the mechanism of TA has been debated (J.A.G. Singleton et al. 2013), there has been little analysis of the mechanism of blast PI to date. The association of pelvic disruption to fatality in those with lower extremity wounds is evident from this data analysis, therefore this injury pattern requires further analysis. Flail of the lower limb may be a causative mechanism in PI, with the rapid lateral separation of the limb causing disruption at pelvic joints. Therefore, prevention of flail in the lower extremities may be key in designing future, or improving current protective measures. Further analysis is required to establish the exact PI patterns present in blast injury in association with these amputations to the lower extremity. In order to tailor mitigation, it is important to ascertain whether the majority of these casualties are injured on foot, or in vehicle, therefore focussing on either applied personal protective equipment, or vehicle design accordingly.

Considering the majority of the fatalities were killed in action, as demonstrated by other studies (Keene et al. 2015), the focus on prevention of injury rather than improvements in the patient treatment pathway will yield the most survivors. Indeed, future conflicts are unlikely to see the rapid evacuation times and prompt surgical intervention that were made possible in Afghanistan (Ministry of Defence 2015).

Therefore, unless injury burden can be reduced at the point of injury, in the event of a similar conflict, if no further progress is made in mitigation, survival rates will not improve, and may even reduce if evacuation times are lengthened.

There are inherent limitations associated with a retrospective analysis such as this, however, the data set was prospectively collected at the time of patient wounding and treatment; true prospective studies are difficult in conflict due to the operational environment and high level of activity. The database used here provides highly accurate injury data due to routine CT scanning of all injured casualties in the deployed operating environment.

3.6 Conclusion

This chapter confirms previously published work, that the more proximal the TA, the higher the fatality rate, and adds the information that although bilateral amputation does increase mortality compared to unilateral, the level of amputation is a more significant contributor to the likelihood of dying of wounds. The analysis also demonstrated that PI was the most important determinant of fatal injuries in the cohort of patients with lower extremity wounding from explosives. The link between PI and TA is very important, and must be considered when developing mechanistic hypotheses. The following chapter will further discuss PI details in blast, and establish from the published literature the high incidence of fatality in PI and further analysis that is required to fully understand this injury pattern.

CHAPTER 4

LITERATURE REVIEW: PELVIC INJURY IN WARFARE

The previous chapter presented the largest database of lower extremity injuries and TAs to date, with an accompanying analysis of fatality in this casualty group. This evaluation concluded that although there was an increase in survivability of TA throughout the course of the conflict in Afghanistan, fatality rates remained high, even in the final year of the conflict. PI was identified as the most significant contributor to fatality in the blast casualties that sustained a TA, and highlighted the need for further research specifically focusing on this injury pattern. This chapter analyses the pelvic injury literature to describe relevant anatomy, diagnosis, and assessment and management of PI.

4.1 Introduction

PI in both civilian and military casualties is associated with a high ISS and mortality (Mossadegh 2012; Sathy et al. 2009). Considerable force is required to cause pelvic disruption, and therefore there is a strong association with additional trauma to other body regions (Chong et al. 1997). Unless the mortality is secondary to wounds elsewhere, mortality from PI is primarily due to haemorrhage, and this is arterial, venous or a combination depending on the exact site of pelvic trauma (Cryer et al. 1988). The mechanically unstable pelvis with haemodynamic compromise is a life threatening condition, although fortunately relatively rare in the civilian setting, only 1-2 per cent of PIs presenting to civilian major trauma centres (MTCs) (Gänsslen, Giannoudis, and Pape 2003a; Hak 2004). Therefore some centres do not see high volumes of severe PIs and consequently, these injuries can pose a challenge to the receiving medical teams (Moreno et al. 1986).

As presented in the previous chapter, PI in association with lower extremity injuries in the recent conflicts in Iraq and Afghanistan due to blast significantly elevates mortality rates in those with lower extremity wounding. PI is particularly common in traumatic amputees, and the combination of TA and PI was a common occurrence in the recent conflicts, and termed the 'signature injury' (Ramasamy et al. 2008). The mechanism for this injury combination is not yet fully understood. While the previous chapter outlined patterns of TAs and the link to mortality, the exact injury patterns within the scope of blast PI has not yet been established, nor has a mechanism been postulated for the link between traumatic amputation of the lower limb and the presence of PI. It is important to document the effects of blast on injury severity and likelihood of death, in order to direct treatment appropriately for future incidents involving high velocity wounding, in civilian and military cohorts.

4.2 Anatomy

The pelvic ring is a stable structure consisting of strong, vascular, cancellous bone comprising of the sacrum, coccyx, bilateral iliac, and ischial bones (Figure 4.1).

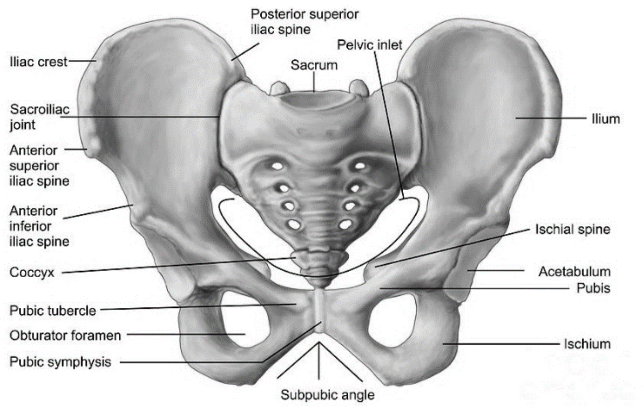
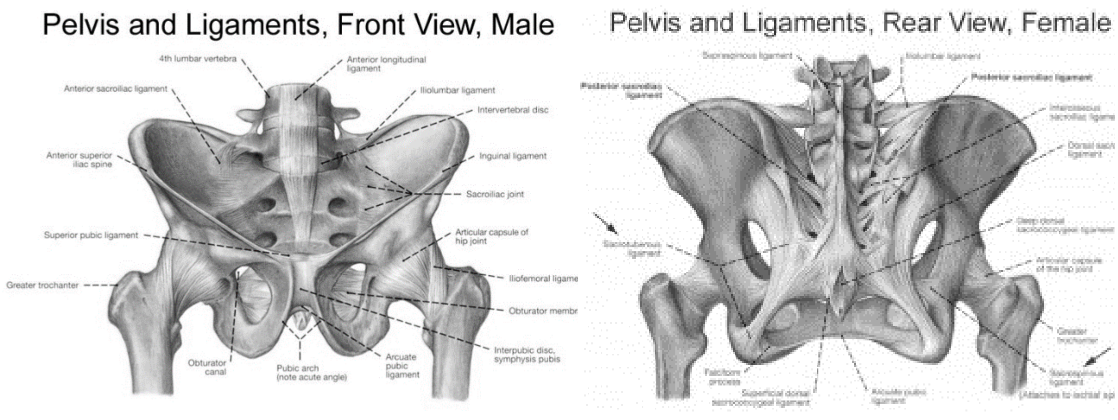


Figure 4.1: The Bony Pelvis. Adapted from: (edoctoronline.com/medical-atlas 2017).

The pelvic joints and ligaments provide considerable reinforcement to the pelvis. (Figure 4.2). Anteriorly (Figure 4.2(a)), the PS, a very robust secondary cartilaginous joint, fuses the pubic bones in the midline. Posteriorly (Figure 4.2(b)), there is a complex network of ligamentous attachments and two joints; the synovial SIJs and the sacrococcygeal joints, which are secondary cartilaginous. The ligaments comprise of anterior and posterior sacroiliac ligaments, with the intraosseous sacroiliac ligaments underlying. The anterior sacroiliac ligament runs from the anterolateral part of the sacrum to the auricular surface of the ileum. The posterior sacroiliac ligament is in two parts. The superior part is short and almost horizontal linking the posterior tubercles on the back of the sacrum to the tuberosity of the ileum. The inferior portion connects the third tuberosity of the sacrum to the posterior iliac spine, travelling in an oblique direction. The sacroiliac joint complex is a robust system with strong viscoelastic properties providing powerful resistance to joint opening. The sacrotuberous ligament blends with the posterior branch of the posterior sacroiliac joint, and attaches the sacrum with the ischial tuberosity, the sacrum and the ischial spines. Iliolumbar ligaments attach at the lumbar vertebrae and the wing of the ileum superiorly (Figure 4.2).



(a) (b)

Figure 4.2: The Bony Pelvis: Anterior and posterior pelvic ligaments. Adapted from (edoctoronline.com/medical-atlas 2017).

The muscles of the abdominal wall, back, buttock and pelvic floor provide less contribution to the strength of the pelvis than the bones and ligaments, but are likely to be significant. Intra-abdominal organs such as the bladder (which is variably fluid filled), and the bowel (which contains either air, fluid, or solid matter), can also be variable in their volume and constituents. Differences in volume and states of matter at any one time may not affect pelvic injury in these high loading rates observed, but the contribution of the soft tissues to pelvic biomechanics, which although may not be significant, is not known.

4.3 Classification of Pelvic Injury

PI has been classified, initially by Pennal and Tile (Pennal et al. 1980), and later modified by Young and Burgess (Burgess et al. 1990a), to relate direction of force applied to the pelvis, with the injury patterns this creates. These are classified as: anterior posterior compression (APC), Lateral compression (LC) vertical shear (VS) and combined mechanism (CM) (Figure 4.3).

APC injuries occur typically from high impact injuries, typically motorcyclists impacting the fuel tank, and crush injury (Dalal et al. 1989a). In this mechanism, one iliac blade is externally rotated, causing disruption at the pubic symphysis and disruption of the sacroiliac joint on the ipsilateral side. These can be graded into severity with type I being isolated widening of the symphysis pubis of up to 2.5cm with no disruption of the SIJ. Type II involves >2.5cm of PS widening and only anterior SIJ widening. Type III injuries are comprised of anterior and posterior sacroiliac ligament disruption with disruption and widening of the PS by >2.5cm(Burgess et al. 1990b). In APC injuries, the casualty is more likely to sustain severe vascular disruption from the iliac vessels that cross the SIJs, and mortality has been shown to be secondary to this, as opposed to additional injuries, as in other injury patterns (Dalal et al. 1989b).

LC injuries are typically crush, or lateral impact sustained in motor vehicle collisions (Dalal et al. 1989a). These are also sub-classified into I, II and III (Burgess et al. 1990b). Type I injuries occur if the force is directed to the posterior portion of the pelvis, sometimes causing crushing of the sacrum at the foraminae, the weakest area. This rarely causes ligament disruption and so is considered a stable injury. Type II and III injuries are caused by compression at the anterior portion of the pelvis, and internal rotation of the iliac crest occurs, and in addition to sacral crush injuries, injury of the posterior ileum can occur. Type III injuries are caused by significant force which projects one iliac crest into the contralateral, causing external rotation of that contralateral pelvis, with disruption of the SIJs (Young et al. 1986). Casualties with LC injuries are more likely to sustain fatal injuries elsewhere as opposed to their pelvic injury being responsible for death, and this is most likely to be head injury, thoracic trauma, or injury to the solid abdominal organs (Burgess et al. 1990a).

VS injuries occur when a vertical force is transmitted though the pelvis, often from a fall from height, landing feet first. The sudden deceleration caused the sacrum to remain in situ, and ileum to be displaced superiorly. CM injuries involve any combination of more than one of APC, LC or VS injuries.

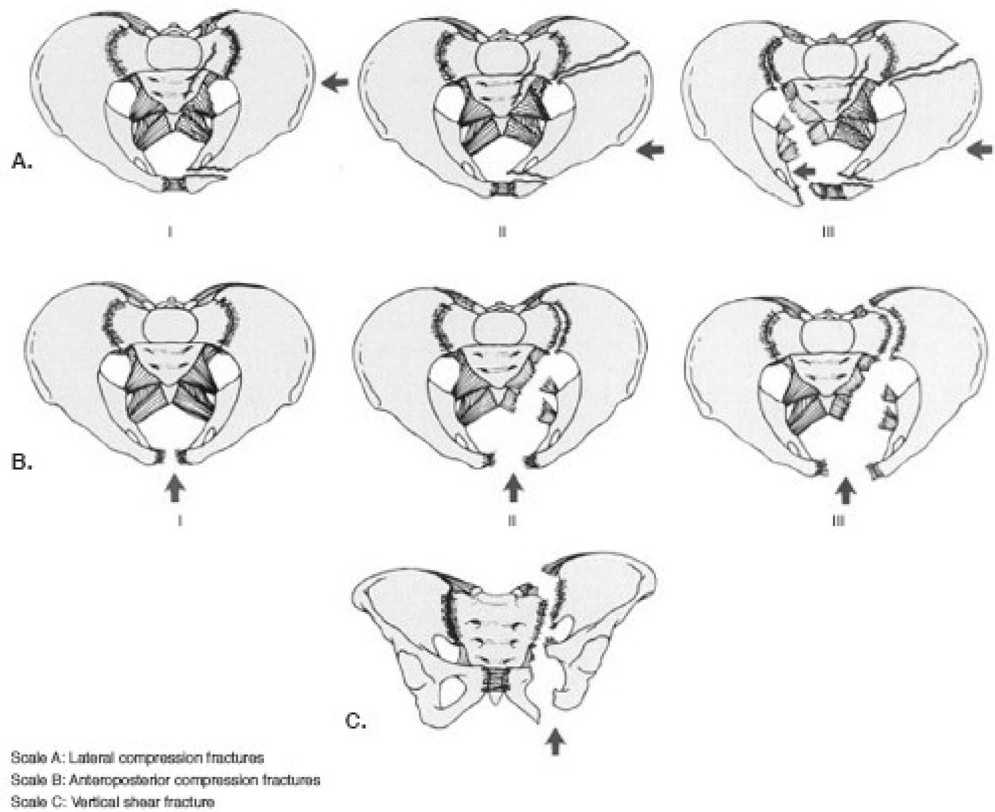


Figure 4.3: The Young-Burgess Classification of Pelvic Injuries. Adapted from: (Burgess et al. 1990b).

Establishing whether the disrupted pelvis is mechanically 'stable' or 'unstable' is important. The pelvis can be either mechanically stable (APCI, LCI); horizontally unstable (APCII); vertically unstable (LCII), or both horizontally and vertically unstable (APC I, LCIII, VS). Whether the pelvis is mechanically unstable is key for subsequent clinical management. The unstable pelvis creates both a greater pelvic volume in which exsanguination can occur, and subsequent closure of the pelvis can result in a tamponade effect which slows bleeding. In addition, fixation of the pelvis prevents ongoing injury to surrounding structures on casualty transfer (Blackmore et al. 2014). It has been demonstrated to be difficult to diagnose the mechanically unstable pelvis by clinical examination alone, and cross sectional imaging is required to confirm this diagnosis (Shlamovitz et al. 2009).

An additional method of classifying injuries is the Arbeitsgemeinschaft für Osteosynthesefragen (AO) classification of pelvic injuries. The AO group was founded in 1958 as a group of Swiss surgeons with an interest in orthopaedic trauma, which has since become a worldwide community of subject matter experts. The AO classification of pelvic injuries offers similar information on ring stability to the Young-Burgess and Pennal and Tile classifications (Figure 4.4).

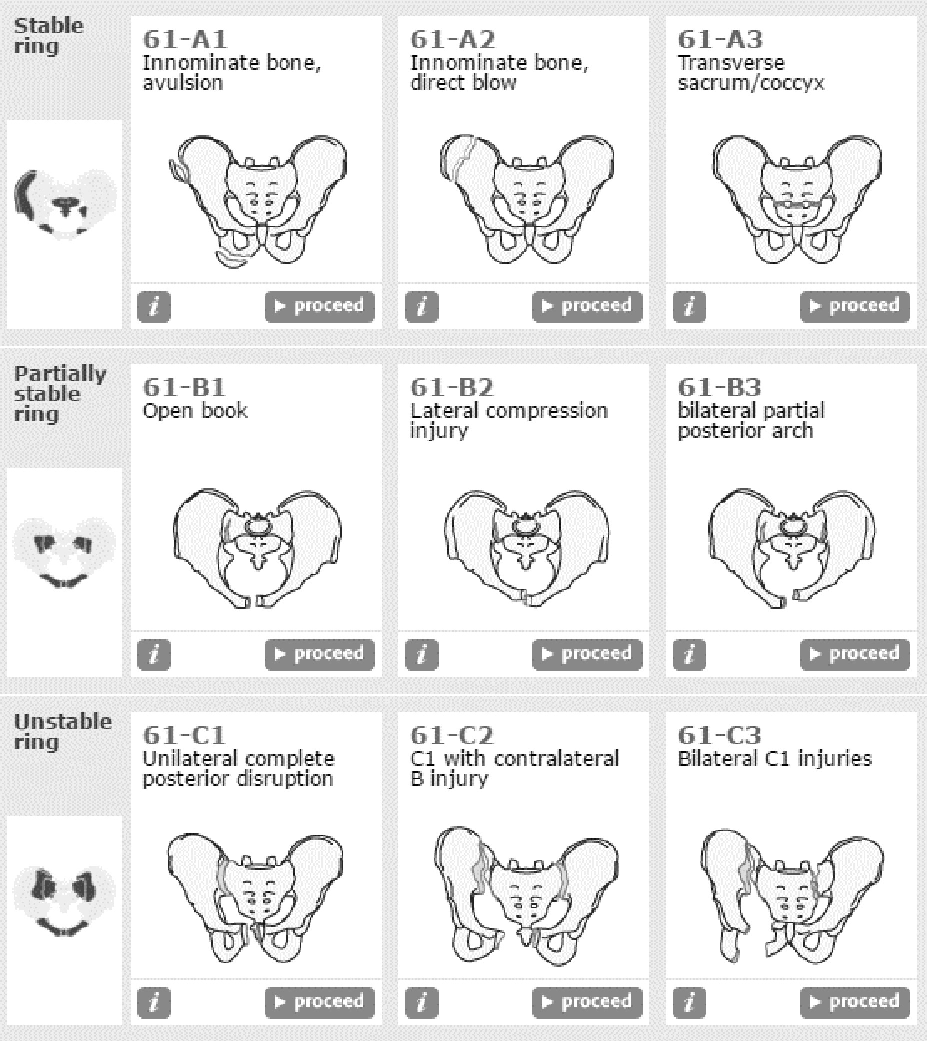


Figure 4.4: The AO Classification of Pelvic Injuries. Adapted from: (Https://www2.aofoundation.org 2014).

This AO classification system also adds further variables such as the location of anterior or posterior disruption, either through joints or bony structures, and this is helpful in guiding treatment plans.

Bony injury to the pelvis alone is not fatal; however it is a marker of injury severity, and it is the damage to surrounding structures, particularly abdominal viscera and blood vessels, that causes fatalities. It is therefore important to understand the anatomy of the pelvic vasculature, as well as the injury patterns that may lead to specific vessel injury.

4.4 Haemorrhage in Pelvic Injury

The pelvis has a rich network of vasculature (Figure 4.5), and it is easy to recognise why pelvic injury can cause significant disruption to vessels, which can contribute to significant blood volume losses.

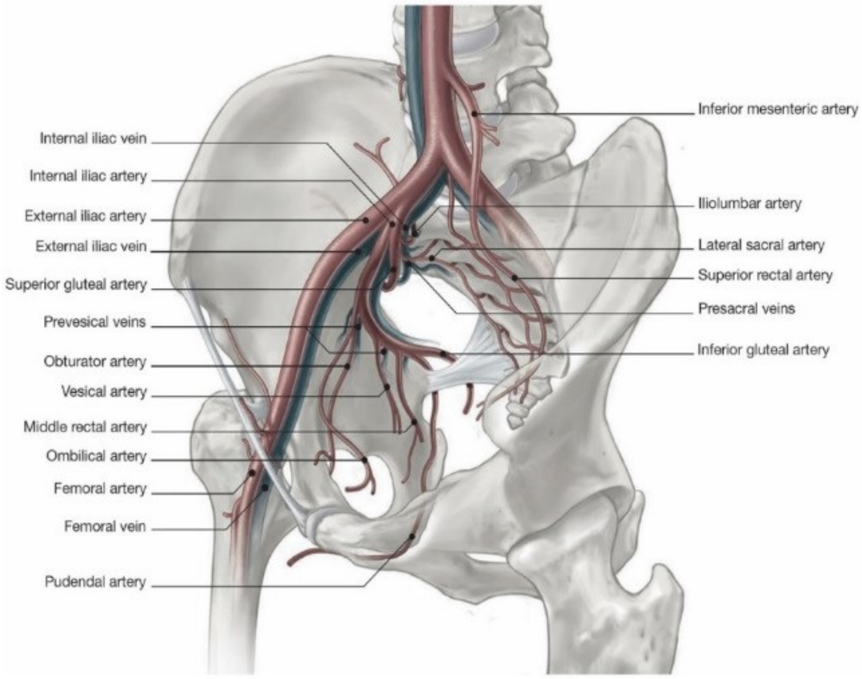


Figure 4.5: The Vascular Network within the Pelvis. Adapted from: (Hitachi Healthcare 2017).

Venous haemorrhage is responsible for the majority of pelvic bleeding due to trauma, reportedly responsible for up to 90 per cent of pelvic trauma cases with associated haemorrhage (Gänsslen, Giannoudis, and Pape 2003b). This results in bleeding in the retroperitoneal space where the vessels lie. The retroperitoneal space is relatively fixed, and this can provide local tamponade if the pelvic volume is normal. In the event of either breach of the retroperitoneum, or mechanical instability, the retroperitoneal space can increase in volume and therefore, tamponade will not occur, and the casualty will continue to bleed unless treatment is initiated.

4.4.1 Location of Vessel injury in Pelvic Fracture

Vessel locations can be divided into anterior and posterior zones depending on their location within the pelvic ring (Table 4.1).

Division	Branch
Anterior	Obturator
	Inferior Gluteal
	Pudendal
	Haemorrhoidal
	Inferior Vesical
Posterior	Superior gluteal
	Lumbar
	Sacral

Table 4.1: Anterior and Posterior Division Pelvic Arteries.

There have been several attempts to link injury patterns with sites of bleeding, however, there are only few, recent, large, multicentre studies. Internal iliac bleeding and bleeding to the posterior branches (gluteal, superior rectal, and sacral arteries) are likely to be more common in APC injuries, and LC injuries tend to be associated with anterior division arteries (mainly pudendal and obturator) bleeding (Ben-Menachem et al. 1991)(O'Neill et al. 1996). However, a larger trial relating pelvic bleeding to stability demonstrated that stable pelvic injuries can bleed form either anterior or posterior divisions, and unstable injuries can bleed from posterior divisions (Metz et al. 2004). In general, using the Burgess classification, the pelvic injury pattern can allow prediction of the likelihood of a vessel injury, based on the structures surrounding the injury, and this can be done fairly predictably based on plain radiology (Niwa et al. 2000). However, pelvic fractures in military casualties are more extensive and may not fit into a set category (Ramasamy et al. 2012a). The casualties are often injured in multiple body regions, and may be hemodynamically compromised secondary to injuries elsewhere, therefore management decisions are often complex. In military casualties, a classification into 'zones' of haemorrhage has been created (Pedersen et al. 2013).

However, this does not distinguish between arterial and venous, and specific locations, which would have diagnostic and treatment implications.

Any significant pelvic bleeding can cause the well described 'coagulopathy of trauma (Hess et al. 2008). Coagulopathy of trauma is an impairment of haemostasis following major trauma resulting in rapid consumption of clotting factors, and subsequent disorders of blood clotting (Frith et al. 2010). Unless rapid transfusion of blood and blood products is administered, as well as haemorrhage control with an appropriate method, this is highly likely. Shock will also increase the incidence of sepsis, Acute Respiratory Distress Syndrome (ARDS) and therefore mortality (Siegel et al. 1990).

4.4.2 Control of Haemorrhage in Pelvic Injury

Venous haemorrhage

As noted above, the majority of pelvic haemorrhage in civilian injuries is secondary to venous bleeding. Bleeding due to venous disruption can be treated in the initial phases with pelvic reduction and stabilisation to reduce the pelvic volume. At the point of injury this is managed using a pelvic binder across the greater trochanters, to reduce, or 'close' the pelvis (Bonner et al. 2011), or operative reduction and internal fixation. Stabilisation of the unstable pelvis aims to achieve haemostasis primarily by restoring normal anatomy, but also secondarily by compressing injury sites to reduce bone bleeding, stabilise early clot formation, and to prevent pelvic volume expansion causing additional bleeding into the retroperitoneum, the latter reported to be the most important in controlling blood volume losses (Velmahos et al. 2000). Venous bleeding, if low volume, can cease with pelvic stabilisation alone, and selective non-operative intervention can be employed with effective monitoring. If venous bleeding continues, laparotomy can then be performed, large vessels either repaired or ligated, and packing of the pelvis performed for indiscriminate oozing with large swabs to tamponade bleeding points in the retroperitoneal plane (Figure 4.6). These packs are later removed when bleeding has ceased.

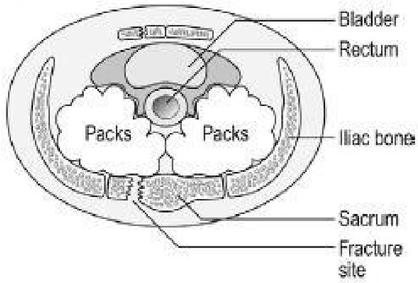


Figure 4.6: Technique of extra peritoneal packing. Reproduced with permission from N Tai, Consultant Surgeon, Royal Army Medical Corps.

Arterial Haemorrhage

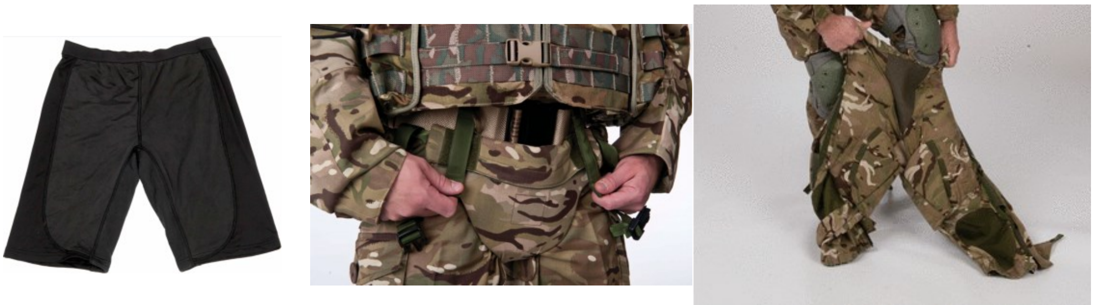
Higher pressure arterial haemorrhage is less likely to be controlled by pelvic fixation or pelvic packing, and requires direct operative repair, ligation, or angioembolisation using interventional radiology. There remains controversy as to whether operative intervention and packing or angioembolisation is the superior method, as both techniques have yielded similar results in terms of survival (Osborn et al. 2009). In the austere environment or department in which angiography is not available, all surgeons must be familiar with the techniques of life saving operative repair.

4.5 Mortality from Pelvic Injury

Reported mortalities rates following PI range from between 7-19% (Starr et al. 2002)(Gustavo Parreira et al. 2000)(Sathy et al. 2009). However, the majority of civilian casualties have fatal injuries remote to the pelvis, either head, chest or bleeding from a solid abdominal organ (Poole and Ward 1994). Most studies linking PIs to mortality have not distinguished those who died specifically from their pelvic injury; the few that do report that the rate is low, between 6-12 per cent (Rothenberger et al. 1978)(Chong et al. 1997)(Demetriades et al. 2002). These studies, however, are based on civilian trauma, and it is potentially inappropriate to compare the outcome of civilian injury to military wounding as the mechanisms of injury are likely very different.

4.6 Military Pelvic Injury

It is known that military wounding, particularly secondary to explosions, are higher energy injuries than the majority of civilian wounding, with a great amount of tissue destruction and contamination (Adams 2009). In a review of 269 casualties with penetrating pelvic injury (Arthurs et al. 2006), the mortality rate was 21%. 54% of casualties had a colonic, and 43 per cent a rectal injury, which were associated with the highest mortality at 33 per cent. 50 per cent of casualties had an iliac vein injury, which was the most common vascular injury, and associated with a mortality rate of 29 per cent. However, the cohort in this analysis focussed on penetrating pelvic injuries, which are likely to have different characteristics than those seen in blast pelvic trauma. Mossadegh et al recognised the high fatality rates of the combination of both pelvic and perineal injury (Mossadegh et al. 2012b) and the need for a more detailed analysis on this injury mechanism. Since the recognition of the combination of high lower limb TA, perineal blast and pelvic injury as a pattern of injury the Defence Clothing (DC) and Personal Combat Equipment (PCE) Teams in Defence Equipment and Support (DE&S) worked with Defence Science and Technology Laboratory (DSTL) to design three tiers of personal protective equipment (PPE). This aimed to protect the groin, perineum, buttocks and upper thigh areas, and is in the form of silk underwear to protect from debris (tier 1), and a Kevlar lined groin piece (tier 2), and knee length Kevlar trousers (tier 3), (Lewis et al. 2013)(Figure 4.7).



(a) **(b)** **(c)**

Figure 4.7: Pelvic protection tiers 1(a), 2(b) and 3(c).

This has been anecdotally successful in protecting against some injuries, particularly genitourinary, but not pelvic injury specifically (Oh et al. 2015). The blast protective garments were not specifically designed to mitigate pelvic injury and it is unclear as to whether it is protective in these casualties. Any personal protective equipment has an effect on agility, energy expenditure and temperature control (Swain et al. 2010) and this has to be taken into account in design of these garments.

4.7 Conclusion

Given the significant contribution of the blast pelvis to mortality following explosions documented in the previous chapter, and the relative deficiencies in the literature on specific topics relating to the blast pelvis, this topic requires further collection and analysis of data. Civilian pelvic trauma has been written about extensively, however, there are likely to be considerable differences between civilian and military injuries. This leaves questions remaining on blast injuries to the pelvis, which merit further study:

a. The specific types of PI patterns from blast injury have not yet been characterised;
b. The mechanism of blast PI has not yet been ascertained;

c. Specific bony injury has not yet been correlated to surrounding soft tissue injury in blast injury to the pelvis;

d. The casualty outcomes specifically from PI characteristics have not yet been fully reported.

The following chapter analyses PI data from the recent conflicts in Iraq and Afghanistan, to determine injury patterns specific to blast, and further understand the cause of the high fatality rates from blast PI.

CHAPTER 5

THE BLAST PELVIS: DATA ANALYSIS

Chapter 4 presented a review of the literature of the diagnosis, assessment and treatment of PI with a focus on high energy injury mechanisms such as blast. It concluded that there was relatively little published work concerning PI specific to a blast mechanism. In addition, due to the relative rarity of severe pelvic disruption in civilian trauma, there is not enough reliable data concerning the mechanically unstable pelvis and surrounding injuries in order to draw comparisons. This chapter presents the data from the conflicts in Iraq and Afghanistan, where PI was a common injury pattern, and assesses injury patterns in more detail than previous studies. The aim is to determine the cause of fatality for those casualties that had sustained PI, and further understand the mechanism of blast injury to the pelvis, in order to find the focus for an injury prevention strategy.

5.1 Part 1: Blast Pelvic Injury Patterns and Environment

5.1.1 Aim

The aim of this study was to identify a cohort of casualties that presented to UK military hospitals having sustained a pelvic blast injury, in order to assesses injury patterns and relate outcome to the environment at the time of injury.

5.1.2 Methods

Data Collection

The JTTR database (see Chapter 3, Section 3.2) was used for this analysis. The database was searched to include all casualties who had sustained a PI from a blast mechanism with an AIS >1 occurring between March 2003 to the withdrawal of British forces in a combat role in August 2014, including conflicts in both Iraq and Afghanistan. Basic patient demographics were obtained including date of injury, age, sex, status (military or civilian) and patient outcomes, as well as injury details as per clinical examination, radiological data, post mortem reports if applicable, and ISS.

As discussed in Chapter 2, (Section 2.3) the environment in which a military injury occurred, either open or confined space, was identified. In these particular conflicts, this equated to being either in a vehicle or on foot, and if injured by either an EFP type blast injury, or a buried IED. For military casualties this is restricted information, as it could be used to expose vulnerability, and so was obtained with the authorisation and guidance of the DSTL. DSTL, also mentioned in Chapter 4 (Section 2.6), is a MOD sponsored organisation who supply science and technology services to government and are involved in risk analysis and assisting with procurement of specialised equipment. They are the custodians of sensitive information such as incident data in casualty situations.

Radiological images were obtained for each patient. In keeping with UK military governance, all fatalities were imaged soon after death by CT (see Chapter 3.1.1), and therefore imaging was available in both survivors and fatalities (James A G Singleton et al. 2013). These images, including those of survivors and post mortem CTs (PMCTs) were reviewed by the author. Detailed PI data was collected. (Table 5.1).

Data Category	Notes
Demographics	
Date of Birth	-
Age at incident	-
Sex	Male/Female
Service	Army, Navy, RAF, Marines, Civilian, Police, Interpreter, Detainee, Contractor
Status	UK Military, Coalition Military, Local Civilian, Coalition, Civilian, Hostile Civilian, Hostile Military, Local Military
Incident Data	
Case Date	-
Country of Injury	Iraq/Afghanistan
Force Provider	Iraq, Afghanistan, UK, USA, Estonia, Georgia, Denmark, Estonia, Uganda, Egypt
Environment at the time of injury	In Vehicle
	On Foot
Injury Data (general)	
Severity Abbreviation	Wounded in Action (WIA) DOW (Died of Wounds) Killed in Action (KIA)
Injury Severity Score	-
Outcome	Survivor/Fatality
Injury 1, 2 and 3 data	Injury codes and scores by Injury Severity, and injury descriptors
Total Injury Number	-
Injury Data (specific)	
Traumatic Amputation	Present/absent, level, unilateral/bilateral
Pelvic injury detail	Pelvic injury location
	Sacroiliac disruption
	Pubic Symphysis Disruption
Vascular Injury	Present/Absent
	Arterial/Venous
	Vascular Injury Location
Perineal Injury	Present/Absent
Treatment Data	
Operations Performed	Description of procedures
Tourniquet Used	-

Table 5.1: Fields Collected for Pelvic Injury Data: Demographics, incident data and injury data both general and specific.

Data analysis

Probabilities for this analysis were calculated using chi squared, due to the categorical nature of the data. Differences in injury patterns in mounted and dismounted casualties were sought, as well as vascular trauma and type of injury pattern present, with significance set at $p = < 0.05$.

5.1.3 Results

Results Overview

Between March 2003 and August 2014, 365 casualties sustained pelvic trauma with AIS >1 from blast. Of these 23 (6.3%) casualties had insufficient data available (for example, no radiological data, poor quality clinical details or lack of follow up) and were therefore excluded. This left 342 casualties who sustained pelvic trauma with full data available.

There were 259 (76%) military and 83 (24%) civilian casualties with an age range of 18-51 (median = 29). Of the 342 casualties, there were 176 survivors and 166 fatalities (48% fatality rate). Of the 166 fatalities, 114 (69%) were KIA, with 52 (31%) DOW, meaning the majority of casualties in this cohort were immediate fatalities prior to medical intervention.

Environment in which Injury was sustained: associated injuries

One hundred and ninety nine (58%) of personnel were dismounted (on foot), with 126 (37%) mounted (in vehicle), and in 17 (5%) the environment in which the injury was sustained was unrecorded. Although there was no difference in the fatality rates (50% vs 50.7%, p=0.911) between mounted and dismounted casualties, there was a higher Injury Severity Score (ISS) and total number of injuries in mounted casualties (median of 50 and 15 respectively, compared with 35 and 11 respectively in dismounted casualties). The most severe injuries, and probable cause of death in mounted casualties were injuries to the head and chest.

In dismounted casualties, injuries to the lower extremities predominated. Therefore, within this dataset, mounted casualties more often died of their associated injuries (72%), rather than PI, and dismounted casualties died predominantly of their lower extremity injury (80%) (p=0.0001). Head injury was the most prolific injury in terms of mortality, however, in terms of frequency, lower extremity injury was responsible for the most fatalities in this cohort (Table 5.2).

	Dismounted (n=199)		Mounted (n=126)	
	Incidence	Fatality Rate	Incidence	Fatality Rate
Lower Extremity	164 (82%)	44%	39 (31%)	25%
Head	19 (10%)	79%	47 (37%)	81%
Thorax	10 (5%)	100%	26 (21%)	22%
Abdomen	6 (3%)	75%	12 (9.5%)	30%
Upper Extremity	0 (0%)	0%	2 (1.5%)	0%

Table 5.2: Main body regions injured, fatality, and environment at the time of injury.

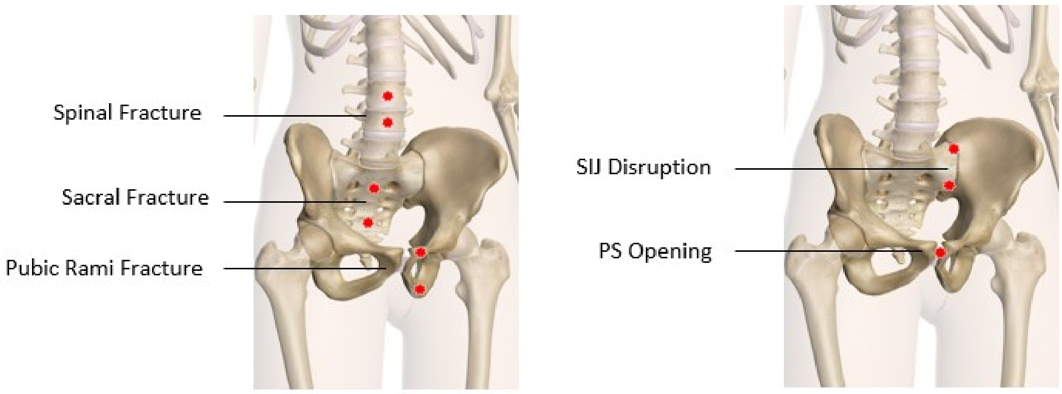
Environment in which injury was sustained: associated injuries: injury patterns

Specific locations of PI were identified from the radiological data, and significant differences were noted between those in vehicle and on foot when injured. The table below presents a comparison of these PI patterns and relevant associated injuries between mounted and dismounted casualties (Table 5.3).

Pelvic Injury	Mounted (n=126)	Dismounted (n=199)	p value
Pubic Symphysis Disruption	42 (33%)	137 (69%)	**0.0001**
Sacroiliac Joint Disruption	42 (33%)	143 (72%)	**0.0001**
Pubic Ramus Fracture	66 (52%)	72 (36%)	**0.0056**
Sacral Fracture	40 (32%)	68 (43%)	0.7173
Spinal Fracture	58 (46%)	40 (20%)	**0.0001**
Acetabular Fracture	40 (32%)	58 (29%)	0.6221
Traumatic Amputation	33 (26%)	152 (76%)	**0.0001**
Perineal Injury	19 (15%)	97 (49%)	**0.0001**

Table 5.3: Injury patterns and environment at the time of injury. Bold values denote statistical significance using chi squared, with significance set at $p < 0.05$.

This table identifies the significant differences in injury patterns to the pelvis, in those mounted or dismounted at the time of injury. These most common injury types in mounted and dismounted casualties are summarised below (Figure 5.1a and b).



(a) (b)

Figure 5.1: Summary of the differences in injury patterns in (a) mounted and (b) dismounted casualties.

5.1.4 Illustrative Images

This data analysis has enabled different patterns of injury in both mounted and dismounted blast casualties to be identified, and therefore it can be hypothesised that a different mechanism of injury may have occurred. This can be illustrated in the following case studies.

Mounted Casualties

As presented in Table 5.3, mounted casualties that have therefore sustained a UBB event demonstrate a predominance of rami fractures, sacral and spinal fractures. No patients mounted at the time of injury sustained destructive soft tissue injuries to the perineum, which is most likely due to the relative protection of the surrounding vehicle, nor did any of these examples sustain a pelvic vascular injury. Neither casualty sustained a TA, or pelvic vascular injury.

Case study 1 (Figure 5.2) sustained a typical mounted injury pattern, with fractured pubic rami, spinal fractures and additional acetabular fracture, iliac blade fracture and no traumatic amputation, but a calcaneal fracture sustained. The pubic rami fracture demonstrated here, is bilateral and involves both superior and inferior rami. Case study 2 is another dismounted casualty demonstrating bilateral sacral fractures (Figure 5.3).

In the same patient, both transverse process fractures and burst fractures of L3 were present (Figure 5.4)

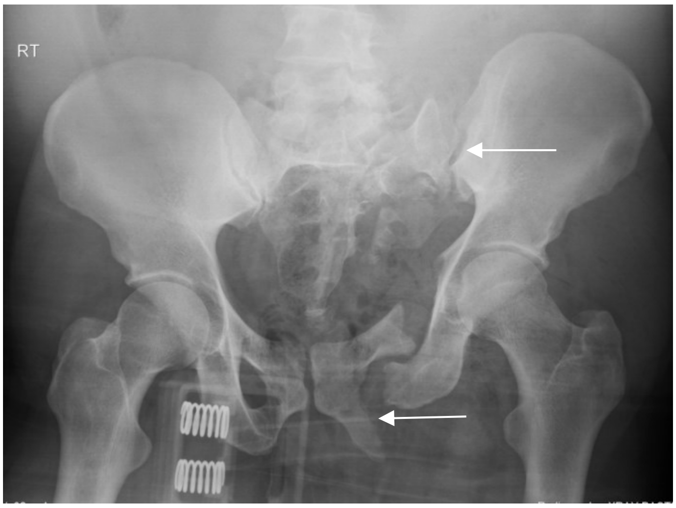


Figure 5.2: Mounted Casualties: Case Study 1: radiograph demonstrating a left superior and inferior rami fracture, and a left scral fracture extending into the left SIJ. Pelvic binder is in situ.

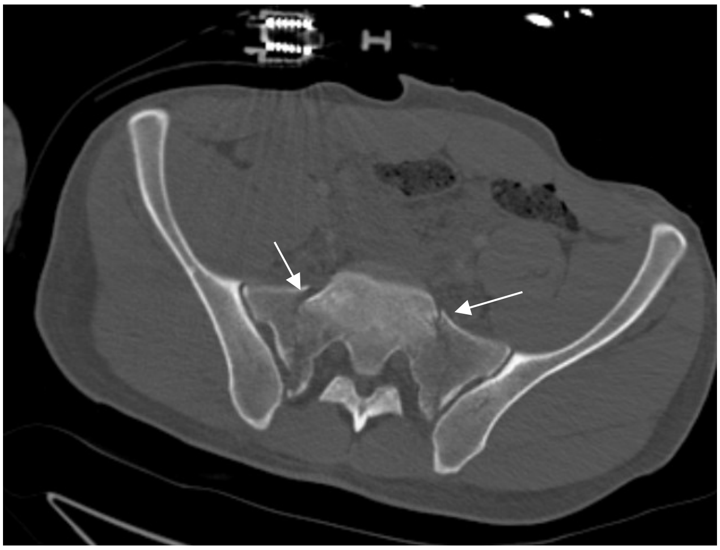
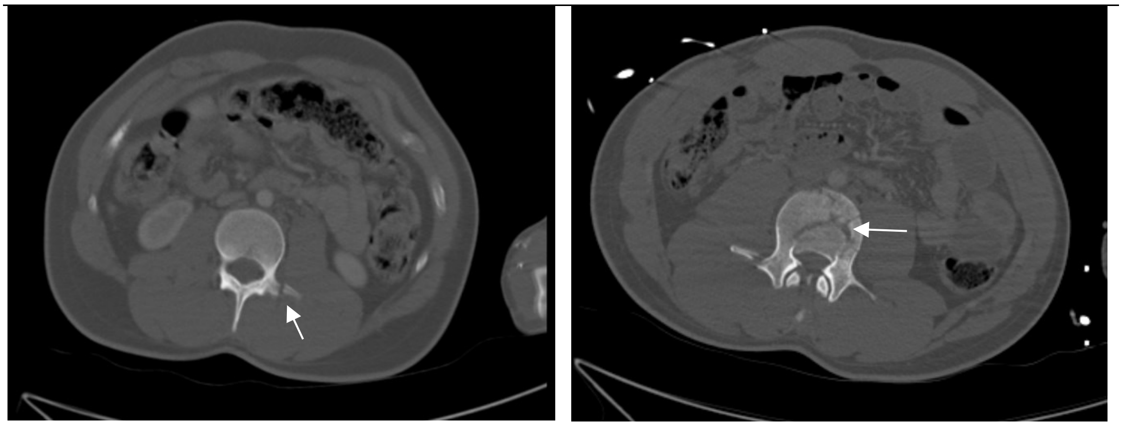


Figure 5.3: Mounted Casualties. Case Study 2 CT scan (axial view) demonstrating bilateral sacral fractures. Pelvic binder is in place.



(a) (b)

Figure 5.4: Mounted Casualties. Case Study 2. Spinal Injury: (a) Transverse process fracture and (b) L3 burst fracture.

Lower Extremity Injuries in Mounted Casualties

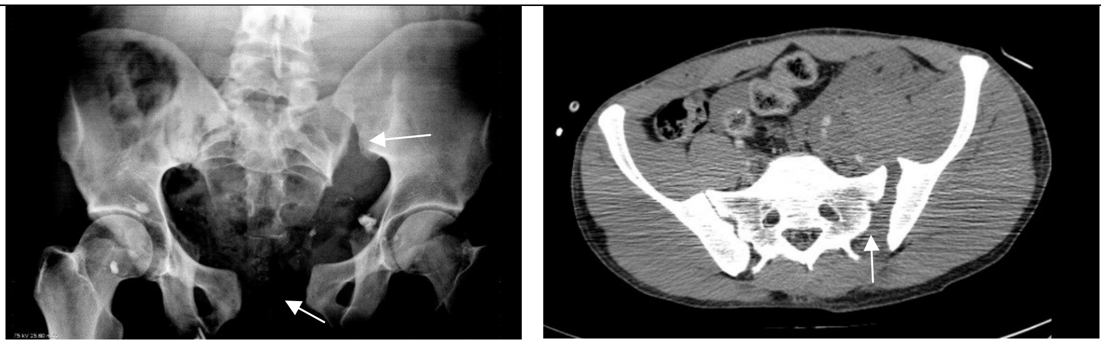
As stated in this Chapter, mounted fatalities subject to IBB are more likely to die from additional injuries to the head or chest rather than to the pelvis, of which their pelvic injuries are not seen to be as fatal as in those dismounted (Table 5.2), and are usually mechanically stable (Table 5.3). Traumatic amputation is uncommon in mounted casualties, however, lower limb injuries occur as fractures due to acceleration of the vehicle floor in underbody blast; tibial and fibular fractures and calcaneal fractures are common (Figure 5.5).

(a) **(b)**

Figure 5.5: (a) Example of a mounted casualty with tibial, fibular and calcaneal fracture. (b) Close-up radiographic image of an exemplar calcaneal injury associated with mounted blast casualties, with the arrow denoting the calcaneal fracture.

Dismounted Casualties

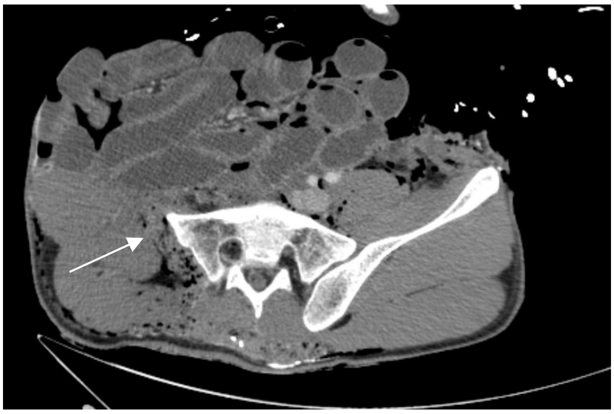
Casualties dismounted at the time of injury demonstrate a predominance of mechanically unstable PI patterns, with disruption at the pubic symphysis and sacroiliac joints, and the high fatality is secondary to vascular injury associated with this injury pattern, with a high incidence of traumatic amputation. The following case studies demonstrate these classical injury types. Dismounted case study 1 (Figure 5.6) demonstrates classical opening of the PS and SIJ. This casualty sustained a generalised pelvic haemorrhage with retroperitoneal haematoma, not attributable to a named vessel injury.



(a) (b)

Figure 5.6: Dismounted Case Study 1. Pelvic film (a) demonstrating disruption at the left sacroiliac joint and pubic symphysis and axial CT scan (with binder now placed) demonstrating the left sacroiliac joint seperation.

One dismounted patient sustained a traumatic hemipelvectomy in association with the entire limb missing on that side. The potential of blast injury to induce complete pelvic separation clearly occurs in the most severe of blast injuries (Figure 5.7).



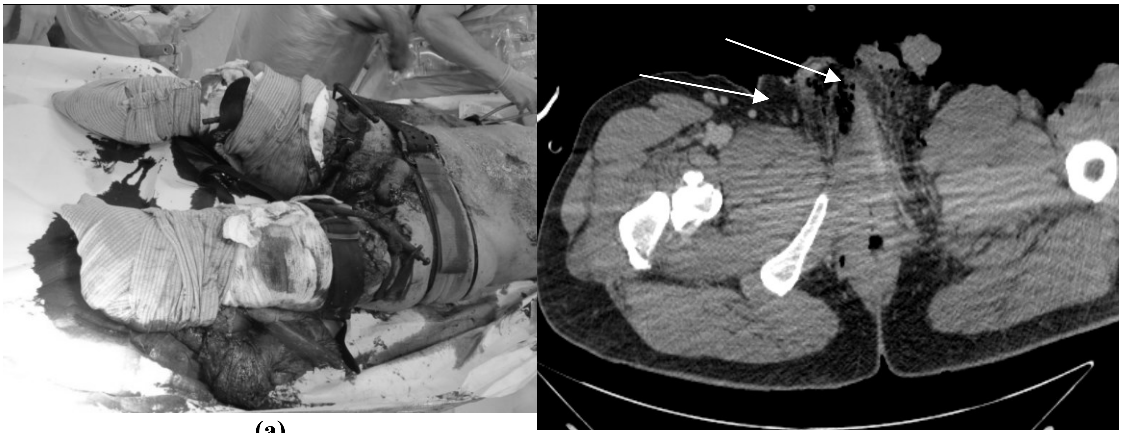
(a)

Figure 5.7: Dismounted Case Study 2. Tramatic Hemipelvictomy axial CT scan. This casualty sustained a traumatic right hemipelvectomy and amputation of the entire right lower limb. There is also substantial soft tissue distruction and abdominal evisceration in this patient.

Lower Extremity Injuries in Dismounted Casualties

As stated in Chapters 3, 4 and this chapter, PI occurs concurrently with TA of the lower limb and soft tissue injury to the perineum. Examples of this is shown in

Figure 5.8. These dismounted casualties are most likely to die from haemorrhagic consequences of their lower extremity injuries rather than from injuries elsewhere in the body, for example to the head or chest (Table 5.2).



(a) (b)

Figure 5.8: (a) Bilateral traumatic above knee amputation and pelvic injury (binder placed) (b) axial CT scan of significant perineal soft tissue injuries.

5.1.5 Implications

These data demonstrate that there is a difference in injury pattern depending on whether the blast incidence occurs in vehicle or on foot. Mounted casualties have a higher overall injury burden by ISS, with fatalities predominantly due to injuries to the head or thorax. Those injured on foot generally have injuries isolated to the lower extremity, with fewer injuries to other body regions, and fatalities are secondary to severe disruption at the lower extremity, including the pelvis. These injuries could be compared to purposeful falls from heights, where a forceful axial load occurs via the lower extremity, for example, suicides, as documented in San Francisco bridge jumping incidents (Lukas et al. 1981). Mounted casualties sustain a wider spread of injury pattern compared to dismounted, with pubic rami and spinal fracture being the most frequent patterns seen. Dismounted victims sustain predominantly disruption at the SIJs and PS, and have a high incidence of TA.

The second part of this data analysis will focus on the fatality of these injury patterns, and assess the areas which will have most effect in improving survivability from the blast pelvis. As identified in Chapter 2, uncontrolled major haemorrhage is the leading cause of death in lower extremity injury. The data analysis in Chapter 3 confirmed this, and implicated uncontrolled bleeding within the pelvis as the leading cause of death in the lower extremity wounding. This chapter suggests that mechanically unstable PIs with major haemorrhage may be important in the dismounted solider but less so in those in vehicle.

In dismounted casualties with PI, major haemorrhage may arise from 4 potential sources: the mechanically unstable pelvis; associated TAs; the extensive soft tissue destruction of the perineum; or direct haemorrhage from injured vessels. This source of haemorrhage is the focus of the next section.

5.2 Part 2: Fatality and Source of Major Haemorrhage in Pelvic Blast Injury

5.2.1 Determining the Appropriate Cohort

The previous analysis presented 342 casualties that had sustained a PI from blast who had adequate radiology available for review. For this next analysis focussing on fatality, those casualties who had more severe injuries elsewhere to the body were removed, in order to ascertain the impact of PI alone on survival, and focus on what would have been the fatal lesions in these cases. Therefore, for this section, 148 casualties were excluded after their injury details were analysed, as they sustained more severe injuries elsewhere in the body (75 head, 27 thorax, 17 upper abdomen, 13 spine, and 16 ‘other’, including burns and drowning). In these patients, the specific outcome from the PI could not be ascertained. The fatality rates were significantly higher in this excluded group (71%, compared with 37%; p=0.0001), due to their additional injuries.

Of the 213 remaining patients a further 34 local nationals were excluded. Their care was subsequently transferred to the local healthcare facilities; therefore it was impossible to determine definitive management or late mortality rate. In addition, unlike UK military casualties the majority of civilian fatalities are not brought to UK medical facilities. Furthermore, civilian survivors who sustained trauma that could be managed by their own health system, AIS 1, 2 and some AIS 3 injuries also may not have been evacuated to UK military medical facilities. Therefore, to remove the bias associated with having missed fatalities, or minor injuries, these cases were also removed.

The resulting dataset therefore comprises of 160 military casualties that have sustained PI without more severe injuries elsewhere, have their full radiology and injury data available, and have comprehensive follow up data. A summary of the process is detailed below (Figure 5.9)

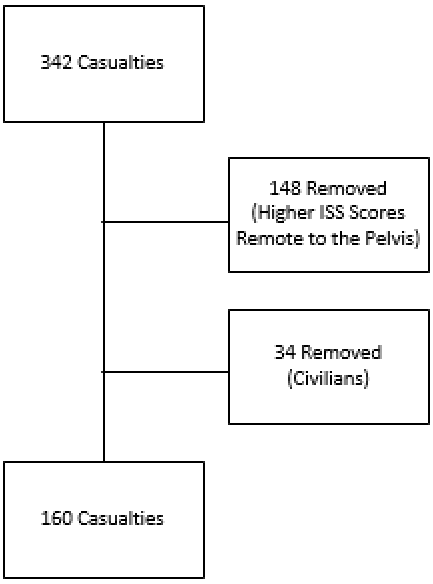


Figure 5.9: Exclusions within the pelvic injury dataset.

5.2.2 Results

Pelvic Injury and Fatality

There were 160 casualties in this cohort (age range 18-49 (median = 28). There were 101 survivors and 59 fatalities (37% mortality). Of the 59 casualties who died, 36 (59%) were KIA, dying before medical care could be initiated. As with the casualties reported in the previous section, prevention of injury rather than improvements in care may be more beneficial in these casualties. Exsanguinating haemorrhage was demonstrated in Chapters 2 and 3 to be the dominating cause of fatality in extremity wounding. In the lower extremity, major haemorrhage can result from an unstable pelvis, TA, perineal soft tissue disruption, or vascular injury within the pelvis. Therefore, fatality rates were considered in these casualties with these injury patterns, with pelvic vascular injury being the most fatal (Table 5.4).

Injury Pattern	Fatality
Unstable Pelvis (n=113)	54 (48%)
TA (n=108)	54 (50%)
Perineal Injury (n=53)	28 (53%)
Pelvic Vascular Injury (n=93)	**59 (63%)**

Table 5.4: Fatality rates of different bleeding sources within lower extremity wounding with pelvic injury. Percentages demonstrate overall fatality of injury types. Pelvic vascular injury is the most fatal wounding pattern (bold).

Fatalities and survivors were subsequently analysed to map the fatalities and survivors with each injury pattern. Pelvic instability, TA rates, perineal injury rates, and the incidence of vascular disruption within the pelvis were all higher in the fatality group, with pelvic vascular injury being the most significant, present in 58% of the casualties overall, but found in 100% of the 59 fatalities (Table 5.5).

Casualties with pelvic injury	Survivor	Fatality
Total (n=160)	101 (63%)	59 (37%)
Unstable Pelvis (n=113)	59 (52%)	54 (92%)
TA (n=108)	54 (53%)	54 (92%)
Perineal Injury (n=53)	25 (25%)	28 (47%)
Pelvic Vascular Injury (n=94)	45 (45%)	59 (100%)

Table 5.5: Fatality and survivor rates of different bleeding sources within lower extremity wounding with pelvic injury. Percentages demonstrate the percentage of survivors or fatalities that sustained that injury type.

Pelvic Vascular Injury

Of the 160 casualties, 93 (58%) sustained a significant vascular injury, in or at the pelvis. Of these subjects, 84 (90%) were associated with disruption at the posterior pelvis, with significant retroperitoneal haematoma, either in association with a major arterial rupture, or generalised venous haemorrhage, with a fatality of 56%. The remaining 9 casualties sustained an anterior pelvic bleed, 8 from femoral arteries at the junction with the external iliac, (a fatality of 10% in this group) and the remaining one casualty sustained an iliac injury from anterior injuries without posterior pelvic disruption (Figure 5.10).

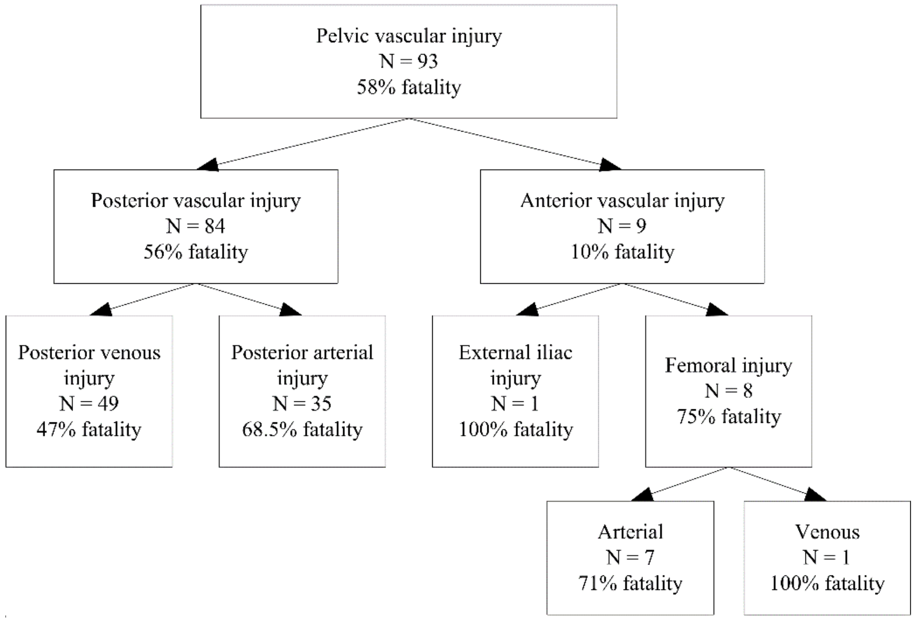


Figure 5.10: Location of pelvic vascular injury and associated fatality.

Pelvic Injury Patterns and Associated Vascular Injury

Given the high incidence of an unstable pelvis the specific bony injury was correlated with the presence of a vascular injury to determine the association of specific elements of the PI to vascular disruption and death (Table 5.6). The mechanically unstable PI pattern with disruption at the PS and SIJs is associated strongly with both fatality and subsequent vascular injury.

Injury Site	Fatalities	Survivors	P Value	Vascular Injury		P value
				YES	**NO**	
Pubic Symphysis Open >2.5cm	51	48	**0.0001**	75	18	**0.0001**
Pubic Symphysis Closed	8	53		23	38	
1 or more Sacroiliac Joint Displaced	51	56	**0.0001**	77	24	**0.0001**
Sacroiliac Joints Non-Displaced	8	45		21	32	
Pubic Rami Injury	19	34	**0.011**	30	45	0.86
No Pubic Rami Injury	12	65		23	32	
Sacral Injury	15	35	0.41	33	46	0.21
No Sacral Injury	19	65		17	38	
Iliac Injury	5	13	0.77	8	69	0.21
No Iliac Injury	27	87		10	45	

Table 5.6: Pelvic injury pattern and associated vascular injury. P values are stated as a relationship between fatality and survivor with injury patterns (column 4) and between injury patterns and the incidence of vascular injury (column 6).

Pelvic Injury and Environment at the Time of Injury

As in Part 1 of this chapter, data were analysed on the environment the casualty was in when the injury occurred, either in vehicle, or on foot. This was to ensure the differences in injury patterns seen in Part 1 were the same when those who died of injuries elsewhere were excluded. Of those casualties sustaining mechanically unstable pelvic injuries, the majority (98%, n=82) were associated with a dismounted posture at the time of injury. Only 4 (17%) of casualties in vehicle sustain the mechanically unstable injury pattern, with the associated vascular injury, while seated. Further analysis was performed to take into account different injury patterns with environment at the time of injury (Table 5.7).

Pelvic Injury n=160	Mounted (n=22)	Dismounted (n=138)	p value
Pubic Symphysis Disruption	6 (27%)	92 (66%)	**0.0001**
Sacroiliac Joint Disruption	9 (40%)	96 (70%)	**0.0001**
Pubic Ramus Fracture	14(63%)	35 (25%)	**0.0001**
Sacral Fracture	9 (40%)	38 (28%)	0.1003
Spinal Fracture	11 (50%)	29 (21%)	**0.0001**
Acetabular Fracture	7 (32%)	17 (12%)	**0.0010**
Traumatic Amputation	2 (9%)	104 (25%)	**0.0001**

Table 5.7: Injury patterns and environment at the time of injury. Bold text indicates significance (p=<0.05).

5.3 Discussion

This study adds new knowledge and understanding of differing injury patterns between casualties injured while in vehicle and on foot. Mounted casualties have a higher overall injury burden compared to dismounted, with fatalities predominantly due to injuries to the head or thorax. Those injured on foot generally have injuries isolated to the lower extremity, with fewer injuries to other body regions, and fatalities are secondary to severe disruption at the lower extremity, including the pelvis. This data also identifies a distinction between the types of PI seen, depending on the environment of the casualty at the point of injury.

Differences in injury patterns between those in vehicle and on foot has been previously described for other body regions in blast, but not for the pelvis until this study (Ramasamy, Hill, Masouros, et al. 2011; James A G Singleton et al. 2013). These differences in injury patterns to the pelvis have not yet been noted in the medical literature, in current nor previous conflicts. This is likely to be because until the recent conflicts in Iraq and Afghanistan with rapid evacuation of rapidly exsanguinating patients, and the widely implemented combat applicator tourniquet, those with dismounted explosive injury sufficient to cause TA and PI would likely have been fatal (Geeraedts et al. 2009). The concept of injury biomechanics and injury prevention in blast, to the level that we see today, using new processes such as blast trauma working groups, post mortem scanning, and injury scene assessment, has provided the ability to understand injury patterns more effectively (Smith et al. 2007b). In addition, modern technologies in terms of sophisticated vehicles aimed to minimise UBB, alteration to PPE, and a wider variety of sophisticated materials means that in these modern times, we have only just begun to have the facilities and process to understand injury biomechanics in blast, and have the ability to mitigate it (Dasch and Gorsich 2016; Wang and Gao n.d.; Zaseck et al. 2017). The mechanisms of these differing injury patterns in mounted and dismounted casualties must be understood if preventive measures are to be employed. Mechanisms of these different injury types in PI are proposed below.

5.3.1 Mechanism of Mounted Blast Injury

Casualties in vehicle at the time of injury, as stated, sustain a UBB event, and sustain predominantly pubic rami and sacral injuries within the pelvis, with a relative absence of injury to the SIJs and PS. This is likely to be due UBB leading to a direct crush effect of the pelvic bones closest to the vehicle seat at the time of the blast injury, and is most likely to be attributed to a tertiary blast effect from the vehicle seat. In addition, when considering the posture of casualties at the time of injury, and the posterior pelvic tilt occurring in the seated position, it is feasible to suggest that load transfer directly from the seat to the pelvic bones is the most likely mechanism of injury in these casualties (Figure 5.11).

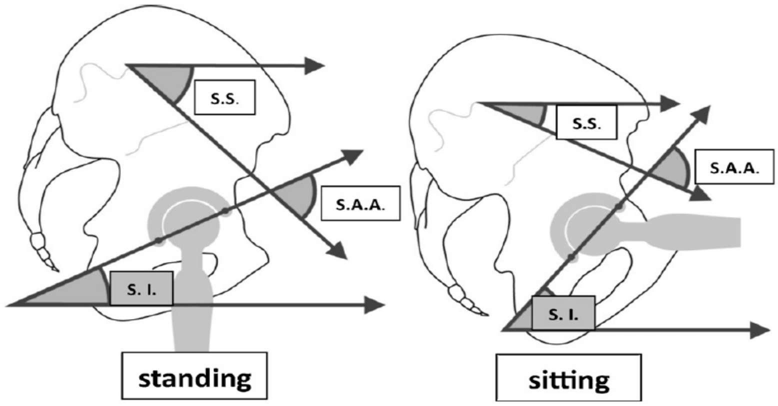


Figure 5.11: Differences in pelvic posture in the standing and seated position. SI=Sagittal inclination SAA=Sacro-acetabular angle and SS=Sacral slope. Adapted from (Chanplakorn et al. 2011).

The posterior pelvic tilt not only brings the pubic rami and sacrum in closer contact to the seat, it also causes the PS to tilt further away from the seat, and therefore, potentially be relatively spared. These injuries of the rami and sacrum tend to be less disruptive than the 'open pelvis' type injury, therefore, load transfer proximally up the torso explains the increase in spinal injuries in mounted casualties. Therefore, the proposed mechanism for mounted blast injury is direct load transfer from the vehicle seat applied to the pelvic bones (Figure 5.12).

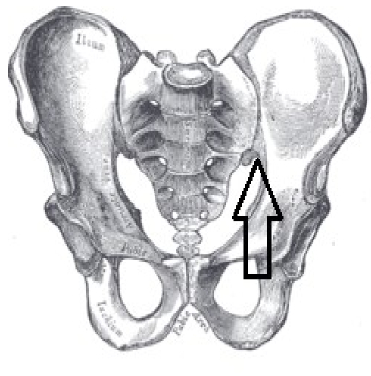


Figure 5.12: Mechanistic hypothesis for pelvic injury in the mounted casualty. Arrow indicates direction of impact due to this UBB event.

The relative lack of TA in the seated casualty also is significant when considering the mechanism of injury. It may be that the presence of load bearing via the lower extremity in the standing position, which is relieved on sitting, is key to causing TA in blast, and also adds the consideration that TA is a causative factor in the open PI pattern, as they seem to occur together. Patients mounted in vehicle are also relatively protected from soft tissue destruction from grit, sand and dirt (sand blast effect), and very few sustain the extensive soft tissue injuries seen in patients on foot while injured from blast. This may also be a factor in TA of the limb in the dismounted casualty.

Mounted injury patterns have been demonstrated to be less prolific and less fatal than dismounted injury patterns, with a lesser incidence of pelvic vascular injury. There is a relative lack of destructive tissue damage as seen in dismounted casualties, and little TA in these casualties. These injuries however, are still important, as they provide key information as to the mechanism of load transfer to the seated soldier in vehicle, and the global burden of tertiary blast injury in vehicle. This research is focussed on improving survivability in blast injury from the pelvis, and therefore no further detailed study on mounted blast injury will occur as part of this research. However, as a result of the findings of this research, further work on understanding mounted blast casualties is being undertaken at the time of writing by other PhD students in the Centre for Blast injury Studies, Imperial College London.

5.3.2 Mechanism of Dismounted Blast Injury

The mechanism of the dismounted blast injury is more complicated than the injury in casualties in vehicle. There are three main injury theories presented below, based on injury analysis and the known effects of the components of blast.

Solid Blast Injury Theory for the Blast Pelvis

The majority of patients, as stated in Chapter 4 that were dismounted at the time of injury, sustain mechanically unstable injury patterns with TA and vascular injury. They also sustain TA in association with their injuries at the SIJs and PS. This type of injury is a much more mortal injury than in the mounted soldier. This injury pattern is unlikely to be due to direct impact at the pelvic bones as they will be remote from the ground in the standing casualty. In addition, TA has been seen to occur even in amputations at lower levels, at the knee and below, therefore indicating that direct impact is not routinely the mechanism of injury (Chapter 3, Figure 3.6). Therefore, load transferred via the lower extremity could be implicated. Axial forces via the femoral head transferred to the acetabulum in a proximal and lateral direction could cause craniolateral separation at the unilateral hemi pelvis (Figure 5.13). This upwards and outwards motion of the lower limb could also be the cause of lower extremity amputation.

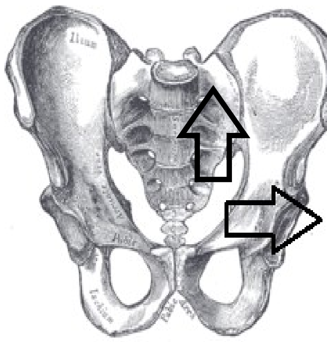


Figure 5.13: Mechanistic hypothesis for pelvic separation in the dismounted casualty. Arrows indicate an upwards and outwards movement of the hemipelvis due to blast.

Secondary Blast Injury Theory for the Blast Pelvis

There is little data in the literature, or experimental studies analysing the destructive potential of fine debris to injuring human tissues. In this dataset, there are many examples of patients who have sustained substantial soft tissue injury with heavy fine fragmentation, which almost strips tissues from bony structures. These are likely to be products of the surrounding environment, sand, dust, dirt and debris, as well as remnants of explosive devices. This injury pattern can be deemed a secondary blast injury due to fragmentation, however, it is most likely to be introduced usually at the 'blast wind' phase of the explosion. This mechanism is an important feature of the dismounted injury, and includes dismounted PI. The review of the case studies in this chapter demonstrated that soft tissue injury to the perineum did have a strong correlation with fatality, however, not to the extent of the open pelvis with vascular injury, so is unlikely to be the primary injury mechanism in the blast pelvis.

Flail Mechanistic Theory for the Blast Pelvis

Lower extremity flail has been postulated as a cause of lower extremity amputation (Doukas et al. 2013), and it could be that the flail mechanism of the lower limb leads to a similar effect in the pelvis. Flail is likely to include an element of both axial load, lateral, and either anterior or posterior forces, depending on the posture at the time of injury, and the location of the device in relation to the body. This resulting superior, lateral and anterior-posterior movement could also lead to pelvic bone separation, and explains the fact that TA and PI often occurs together in blast lower extremity injuries.

The main application of the findings in this research will be the adaptation of PPE to aid in injury mitigation. Secondary blast injury has anecdotally been controlled using the lower extremity PPE introduced midway through the conflict in Afghanistan. If flail is implicated as a pelvic injury mechanism in dismounted blast, then preventative methods could also be employed, to prevent rapid propulsion of the lower extremity, by reinforcement of lateral limb garments, or circumferential support. Solid blast, or axial loading, through to the pelvis is unlikely to be mitigated using PPE. This injury mechanism is therefore important to exclude.

Dismounted blast injury leads to mechanically unstable PI patterns, and is strongly associated with pelvic vascular injury and resulting high rates of fatality due to haemorrhage within the pelvis. Due to this, dismounted PI has been identified as being a high priority for further research focus. Dismounted casualties sustain disruption at the PS and SIJs. Injury to surrounding structures in these injury patterns is highly likely, however, the type and character of injury will be dependent on the type of bony displacement that has occurred. In particular, vascular injury is the key predictor of mortality, and the presence of vascular injury within these injury patterns must be further explored.

5.4 Conclusion

PI in blast has been demonstrated to be an injury with a high risk of fatality, and a potential target for strategies for improvement of survivability. The data analysis in this chapter highlighted posterior pelvic vascular injury, particularly arterial injury, within a mechanically unstable pelvis to be the cause of fatal injuries. This was a feature of patients on foot at the time of injury, with those injured in vehicle sustaining mainly stable PI patterns without vascular injury. Therefore, based on the analysis in this chapter, the focus of this thesis will be the dismounted casualty, as PIs in this casualty group are those that lead to fatality. A mechanistic hypothesis can now begin to be formulated using this data as presented in the discussion of this chapter, but further techniques to further understand this pelvic disruption will help refine these hypotheses. This is the focus of the next three chapters. In the first instance, Chapter 6 will further investigate this mechanically unstable injury pattern seen in the dismounted soldier using objective methods to characterise the direction and magnitude of joint separation that leads to vascular injury and death.

CHAPTER 6

QUANTITATIVE RADIOLOGICAL ASSESSMENT OF PELVIC INJURY IN BLAST

Chapter 4 presented a review of the diagnosis, assessment and treatment of PI with a focus on high rate blast injuries. Chapter 5 subsequently presented the clinical data from the recent conflicts in Iraq and Afghanistan, describing the injury patterns and causes of death, and differences in injury patterns with differing environments at the time of injury. This established that vascular injury at the posterior pelvis is the injury pattern most associated with mortality. This chapter describes methods used for more precise PI measurements in the literature, and then presents an image analysis designed to assess the directional movement of the pelvic bones in blast injury to assess pelvic load transfer in blast, and therefore gain a greater insight into the biomechanics of blast pelvic injury.

6.1 Introduction

PI in dismounted blast casualties has been demonstrated in previous chapters to be an injury with a high risk of fatality due to posterior vascular injury, and a clear target for improvement strategies is required. The injury patterns presented in Chapter 5 described the location of the PIs and related them to vessel injury, known to be the primary cause of fatality. This focusses the interest on SIJ and PS disruption, when vessel injury usually occurs. Although identifying locations of injury that link to fatality is important, what is now required is a quantifiable measure of the level of disruption. There is much variation in the amounts and direction of opening of these two joints in clinical cases of dismounted pelvic blast injury, and it may be that there is a critical amount of joint disruption that leads to vascular injury. If this is known, mitigation to restrict pelvic opening to below this level could be the solution to mitigating pelvic vascular injury in the blast pelvis.

Pelvic classification systems used clinically were described in Chapter 4, and included the Young-Burgess classification (Burgess et al. 1990a), Pennal and Tile (Tile and Pennal 1980), and AO classifications (Schweitzer et al. 2008). These are binary classifications based on the presence or absence of a particular type of disruption, with no specific link made between the direction and distance of disruption and the likelihood of vascular injury. This is important when considering the mechanism of injury, and underlying injury to the soft tissues. Iliac vessel injury in SIJ rupture is likely to be due to movement of the bones in particular directions, and subsequent stresses and strains on the vessels that may not occur at smaller disruptions (Carrillo et al. 1999). For a measurement technique that wishes to describe more accurately how the SIJs move in relation to each other in fracture, and to further understand associated soft tissue damage, an ability to measure the level and direction of disruption is required.

This chapter aims to present finer detail on SIJ and PS disruption by initially reviewing the current literature on existing objective pelvic measurement techniques, and subsequently developing an experimental method to measure the opening of these two joints in order to perform a risk assessment on the likelihood of vascular injury in those with SIJ disruption. The hypothesis is that there will be a distance and direction of joint separation that relates to the presence of vascular injury.

6.2 Pelvic Measurement Techniques: Review of the Literature

Objective measurement techniques for PI described below exist in the literature, and aim to qualify pelvic disruption. They are not used in clinical assessment currently, probably due to the time taken to perform such measurements, and the lack of relevance to clinical management. Measurement techniques, however, are important for understanding the mechanism of injury. The methods available in the literature are presented in the following sections, as well as an assessment of their suitability for analysis of the blast pelvis dataset.

There are several studies which provide methods of accurately assessing the geometry in normal subjects, for example, sacral curvature (Abitbol 1989), the angles between the spine and pelvis (Duval-Beaupère, Schmidt, and Cosson 1992), and posture, gait, and abnormal development (Sadeghi et al. 2000). These serve a purpose in understanding the embryology of skeletal development, anatomical variation, and human posture, and proprioception in the absence of pathology. Objective pelvic measurements such as these are usually developed using a coordinate system on bony landmarks, and these have been used fairly widely in measuring the non-fractured pelvis to assess bony anatomy in both health and disease (Boulay et al. 2006). There are fewer methods for quantifying the disrupted pelvis.

Measurement systems in trauma are often used as an objective measure to monitor pre and post-operative success at fracture reduction. Sagi et al (2009) describe the measurement of ratios between bony pelvic landmarks, with the injured side as the denominator, with a normal value being a ratio of ‘1’ (Figure 6.1). This was used to detect the relative symmetry of the pelvis after trans-foraminal sacral fractures. This method is appropriate for the purpose to which it is intended, however, it cannot be used to measure pelvic openings purely due to SIJ disruption. Furthermore, due to PIs in multiple pelvic regions that occurs in blast, these differences in measurements between the injured and uninjured side could not be assumed to be due to the SIJs, which is the region of interest in the blast pelvic cohort. In addition, this method assumes a normal contralateral side, which cannot be guaranteed in the blast cohort.

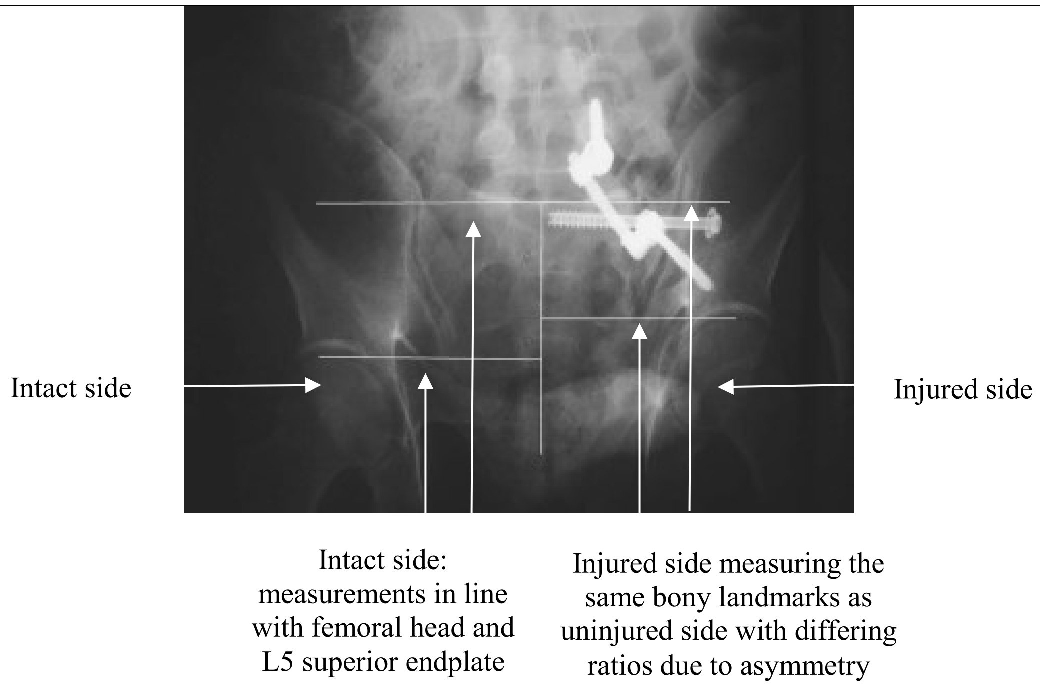


Figure 6.1: The difference between planes created between key bony landmarks of the pelvis using the mechanism described by Sagi et al. 2009. The site of injury can be compared with the uninjured side, and a ratio produced with normal being 1 (the same distances between bony landmarks on each side).

Keshishyan et al. (1995) describe a method of estimating radiographic symmetry in children, by measuring the distance between the lower portion of the SIJ and the internal contour of the acetabular prominence on the contralateral side, with the higher distance values indicating fracture (Figure 6.2). This method is useful for measuring the symmetry of the pelvis, however it cannot attribute differences in symmetry to particular pelvic regions, for example, lateral movement of the iliac wing and the sacrum cannot be distinguished.

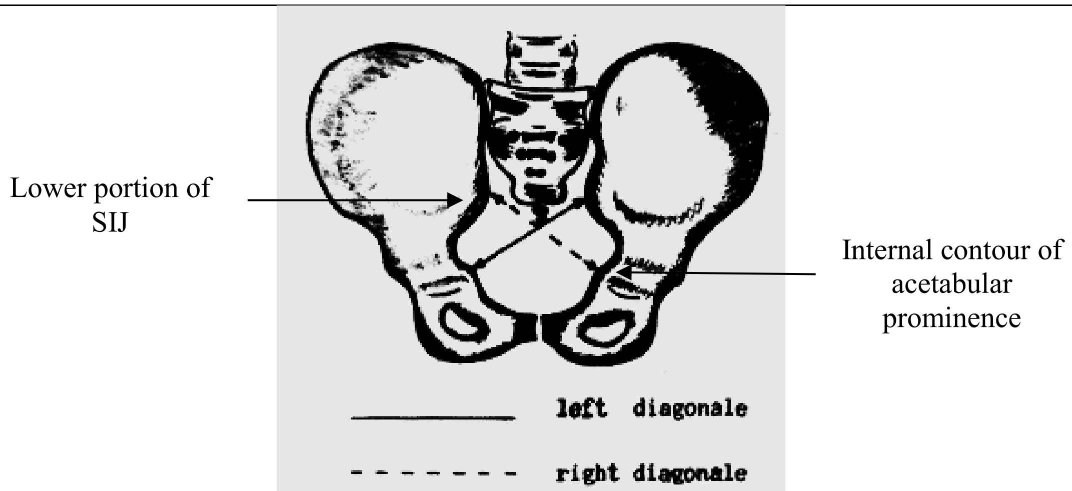


Figure 6.2: A method for measuring inlet symmetry in paediateric patients, with bony landmarks for measurments indicated with arrows. Differences between the lengths of the two arrows indicates asymmetry, with the longer arrow abduction of the that hemipelvis. Adapted from (Keshishyan et al. 1995).

Lefaivre et al (2009) developed the absolute displacement method (ADM), using a horizontal line at the superior endplate of the L5 vertebra to perform measurements using desired anatomical landmarks. This was in order to measure pre- and post-operative bony position, before and after reduction surgery, to assess a successful reduction (Figure 6.3). A method such as this could compare an injured hemipelvis to a normal contralateral pelvis, however, as stated, this is often not the case for injured blast casualties.

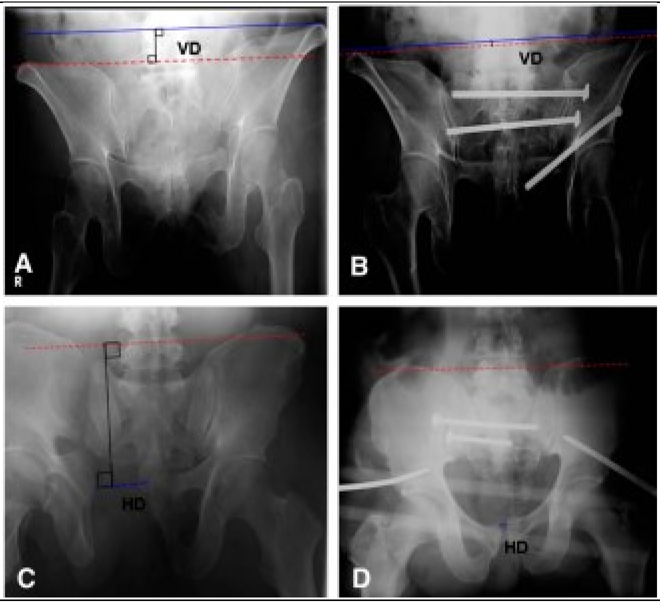
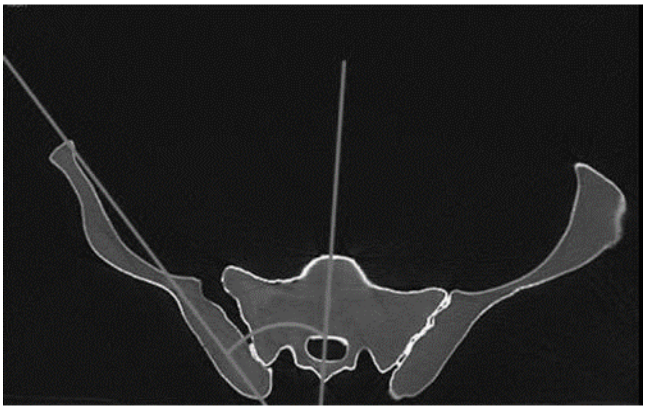
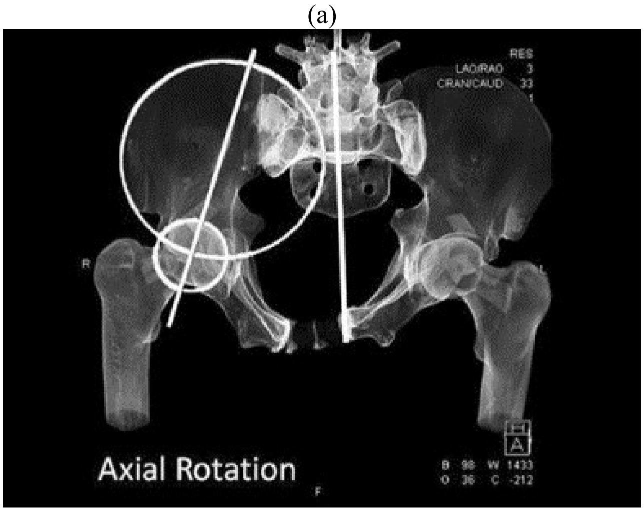


Figure 6.3: The absolute displacement method (ADM) for describing the pre and post operative position of the pelvic bones. (A) prior and (B) after subsequent fixation, and (C) prior, and (D) subsequent to fixation. Adapted from Lefaivre et al. 2014.

Lukas et al (2015) used a sawbone model to create commonly seen pelvic injuries converting CT scans to standardised computer reconstructed radiographs in both inlet and outlet views. They present a technique to measure axial rotation at the inlet view, and sagittal rotation on the inlet/outlet view (Nystrom et al. 2015) (Figure 6.4). The limitation of this study, as noted by the authors, is that it requires an intact ilium, acetabulum and femoral head, which is often not the case for the multiply injured blast patient.



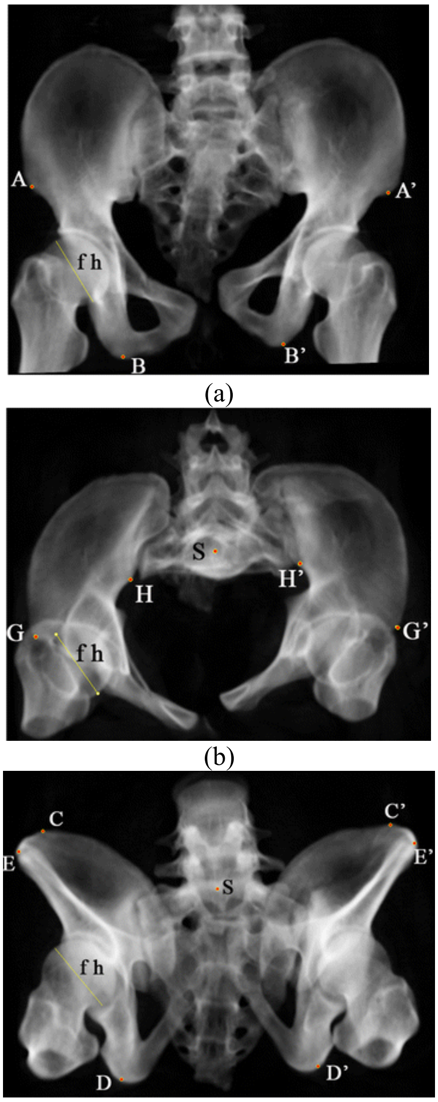
(a)



(b)

Figure 6.4: Radiographic measurement of rotational deformity in pelvic fractures: A novel method with validity and reliability testing. (a) The angle between the mid point of the iliac wing and sacrum as a marker of SIJ widening. (b) measuring axial rotation using the angle between a plane created at the midpoint of the spine, and the mid point of the femoral head. Adapted from Nystrom et al. 2015.

To measure pelvic disruption in injury, Zhao et al (2015) present a method based on using standard CT input and anatomical reference points to recreate plain radiographic images. Pelvic radiographs were constructed in three views: anterior posterior (A-P), outlet, and inlet (Figure 6.5). Two-dimensional coordinates were used to measure the translational and rotational displacement patterns of the injured hemipelvis (Figure 6.5a). In the recreated A-P views, flexion of the pelvis can be determined by a smaller distance between the anterior superior iliac spines (ASIS), and the ischial tubercle, than on the injured side. Similarly, extension of the pelvis could be determined if this distance is longer than the non-displaced side (Figure 6.5b). The inlet views can demonstrate the external rotation of the hemipelvis (i.e. SIJ widening) by analysing the line between the ASIS and the iliac portion of the SIJ. If longer than the uninjured side, the joint is widened, if shorter, internal rotation of the hemipelvis has occurred (Figure 6.5c). Varus or valgus deformities of the pelvis can be determined on the outlet views, where smaller distances between the SIJ and ischial spines indicate a valgus deformation (away from the midline), and larger distances indicate a varus deformation (towards the midline) (Figure 6.5d). This method has been shown to have near perfect reliability (intraclass correlation coefficients (ICCs) of 0.9) (Zhao et al. 2015). This method is an accurate representation of injury patterns and a very suitable method for assessing pelvic disruption in multiple planes using a standardised and repeatable techniques. However, the limitation of this method for the military cohort, is that it relies on an intact contralateral hemipelvis. Many of the blast pelvic fractures within the cohort have bilateral injuries, rendering this method inappropriate for this study.



(a)

(b)

(c)

Figure 6.5: A computer aided measurement method for unstable pelvic fractures based on standardised radiographs (Zhao et al. 2015). (a) A-P view – ASIS: A and A’. Ischial tuberosity: B and B’.) (b) inlet view. ASIS: G and G’. H and H’ anterior border of SIJ. S- sacral endplate (c) outlet view. C and C’ ASIS. S and D and D’ ischial tuberosity. All views: H = femoral head. Adapted from Zhao et al. 2015.

It is evident that none of the previously described methods provide a technique suitable for measuring the injuries seen in the blast pelvis. These methods described require images taken specifically for the study in question, require an absence of additional injuries, for example, to the hip complex, and rely on the use of coordinate systems, and therefore, their use is limited in bilateral injuries. These methods are also not focussed on disruption at the PS and SIJs. Due to these limitations a simple method was developed for the purpose of analysing data from blast injury casualties, measuring disruption of the PS and SIJs in three planes, and relating this to the presence or absence of vascular injury.

6.3 Methods

6.3.1 Requirements

Specific requirements of the measuring technique for the purposes of this study were considered to be:

a. focussed on SIJ and PS disruption;
b. can be used on pre-existing radiographs or CTs;
c. does not rely on an intact contralateral side for comparative measurements;
d. looks at single planes of disruption, so that the data can inform the understanding of pelvic bone movement in specific directions under blast loading;
e. can be used despite multiple injuries of the pelvis.

The aim is to measure the movement of the SIJs and PS in relation to the opposing side of the joint in the anterior-posterior (A-P), superior-inferior (S-I), and lateral directions. This was achieved by developing a technique with the assistance of Colonel Ian Gibb, Defence Consultant Advisor in Radiology, using the measuring tools on the picture archiving and communication system (PACS) used in clinical practice.

This was performed using standard existing images, therefore no new views were required.

6.3.2 Sacroiliac Joints

The SIJs were measured in three planes; S-I, A-P, and lateral. All measurements were taken to the nearest mm due to the slice sensitivity of the images being accurate to 1mm.

Superior-Inferior Displacement

S-I displacement demonstrates the superior or inferior movement of the ilium in relation to its natural position as part of the SIJ. The S-I displacement distance was measured using the most inferior portion of the iliac part of the SIJ, against the most inferior portion of the sacrum in coronal views, in either plain films or CT scans (Figure 6.6,Figure 6.7). This measurement was performed using the plain film, if the resolution in the coronal plane on the available CT scans was not adequate. Examples of this are below. Superior displacement distance is measured in positive numbers, inferior in negative.

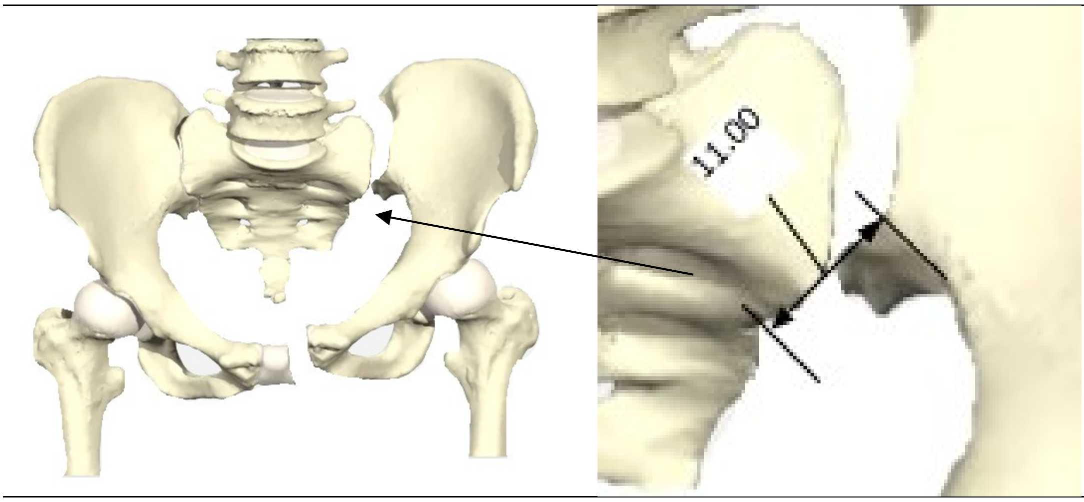


Figure 6.6: The measurement of superior displacement of the hemipelvis, indicated by a positive number (value is +11mm).

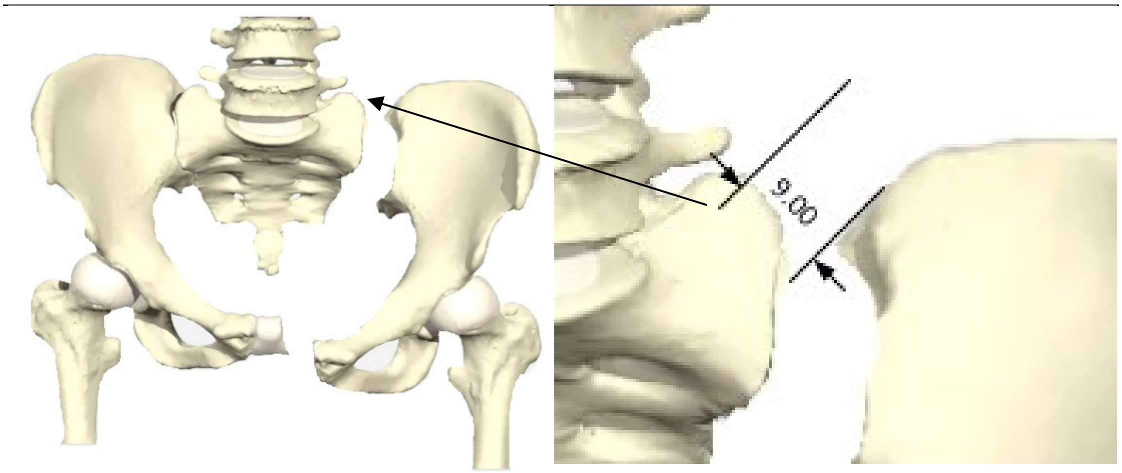
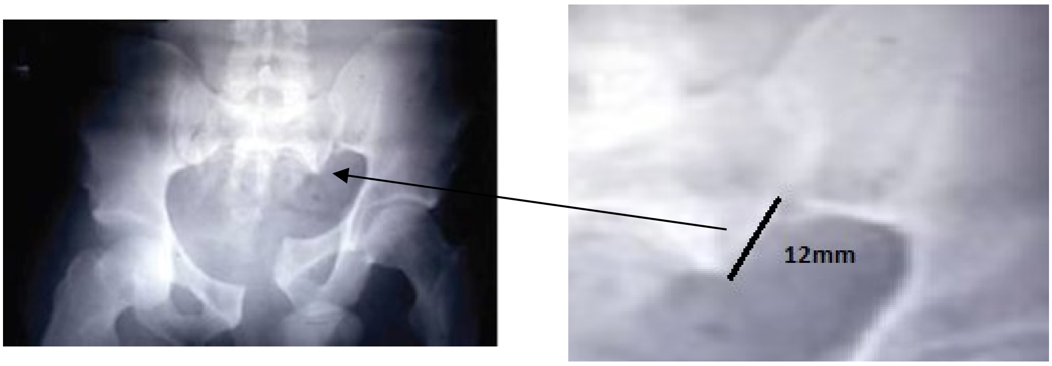


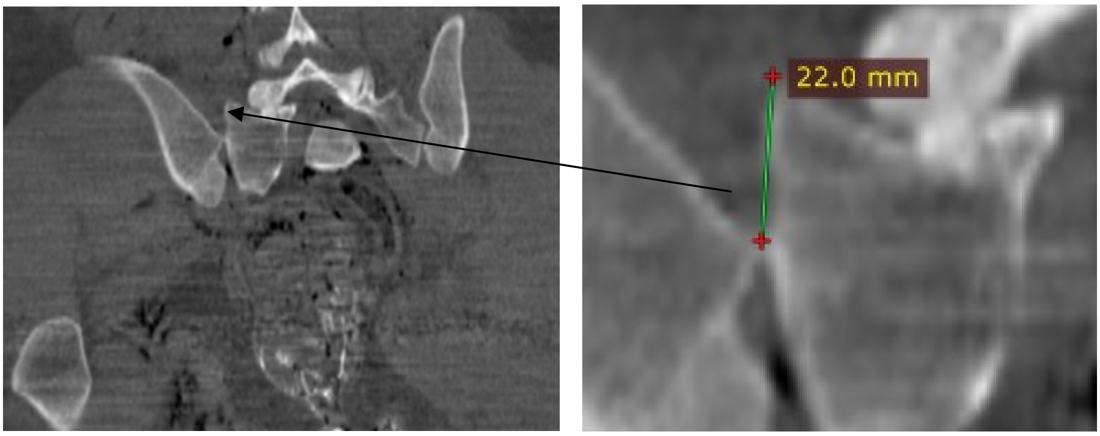
Figure 6.7: The measurement of inferior displacement of the hemipelvis, indicated by a negative number (value is -9mm)

Examples of this measurement in practice in plain radiographs in superior, and a coronal CT in inferior, are demonstrated below (Figure 6.8 and Figure 6.9).



(a) **(b)**

Figure 6.8: Measurement of superior inferior displacement of the sacroiliac joint. (a) Superior displacement of ilium relative to the sacrum. (b) Zoomed in image of the loaction indicated by the arrow showing the measurement of the superior displacement of +12 mm.



(a) **(b)**

Figure 6.9: Measurement of anterior posterior displacement of the ilium (a) inferior displacement of the ilium in relation to the sacrum on CT (coronal view) (b) Zoomed image showing the measurement of the inferior displacement of -22mm.

Anterior-posterior displacement

A-P displacement was measured in axial views in CT scans, using the distance between the most anterior part of the iliac part of the SIJ, and the most anterior part of the corresponding sacrum. Positive numbers indicate an anterior displacement, negative numbers a posterior displacement (Figure 6.10, Figure 6.11). Examples of these measurements are displayed in the following figures, in both anterior (Figure 6.12), and posterior (Figure 6.13) displacement.

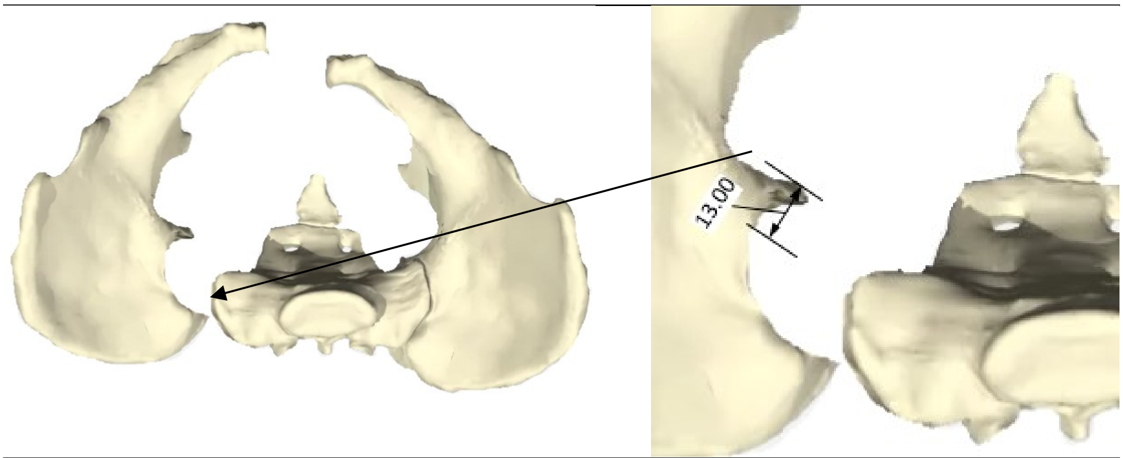


Figure 6.10: The measurement of anterior displacement of the hemipelvis, indicated by a positive number (value is +13mm).

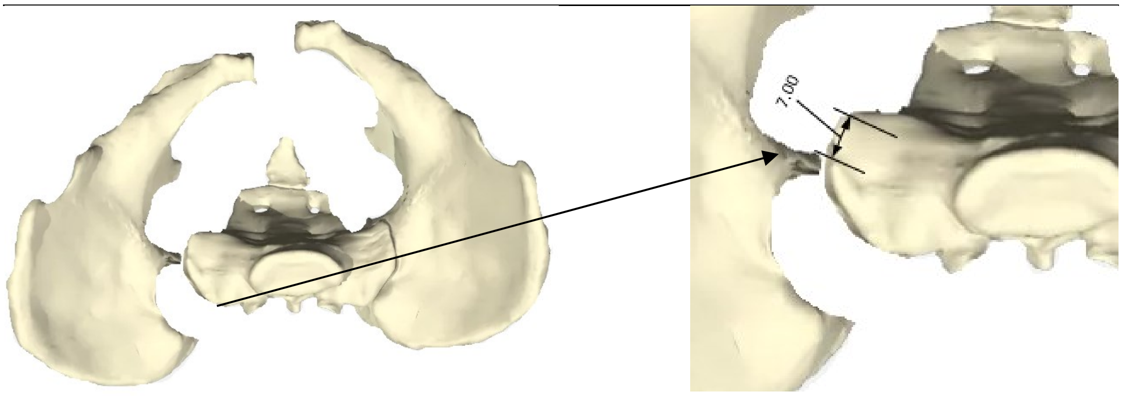


Figure 6.11: The measurement of posterior displacement of the hemipelvis, indicated by a negative number (value is -7mm).

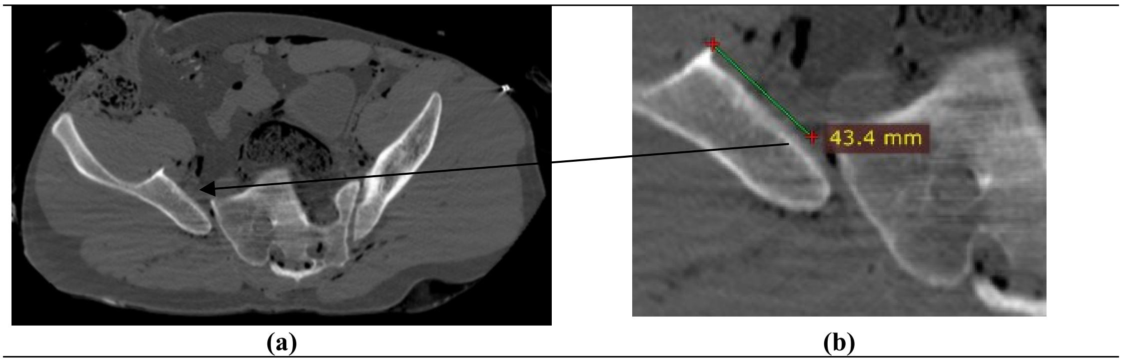


Figure 6.12: Measurement of anterior posterior displacement of the ilium (a) *anterior* displacement of the ilium relative to the sacrum(b) Zoomed image showing the measurement of the *anterior* displacement of +43.4 mm.

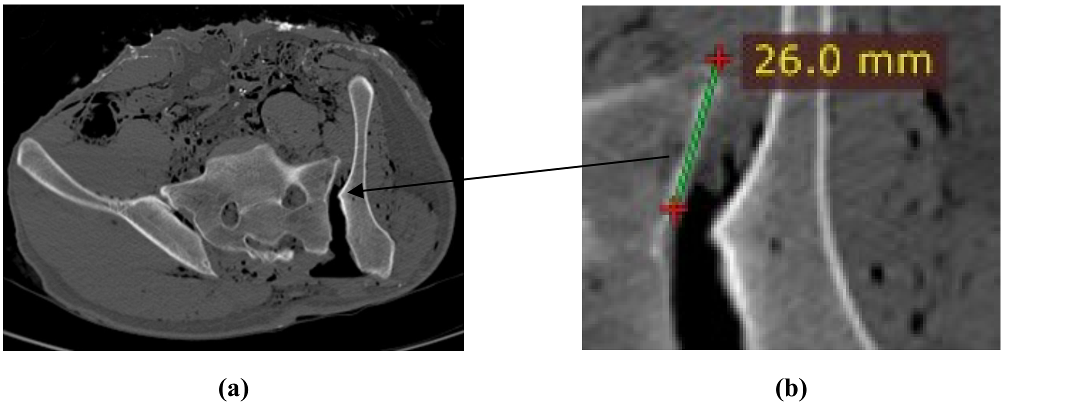


Figure 6.13: Measurement of anterior posterior displacement of the ilium (a) posterior displacement of the ilium relative to the sacrum (b) Zoomed image showing the measurement of the anterior displacement of -26.0mm. Arrow indicates enlarged image of pelvic disruption on the image on the left, with measuring technique on the right image.

6.3.3 Lateral Displacement

Lateral displacement can be measured in both the coronal and sagittal views of the CT scan, and the distance between the joint line varies due to the concavity of the inside of the SIJ. The widest separation of the joint lines was therefore taken to evaluate the extent of SIJ opening in the sagittal view, due to higher resolution of the images in this plane (Figure 6.14). This measurement is demonstrated in the following figure: (Figure 6.15).

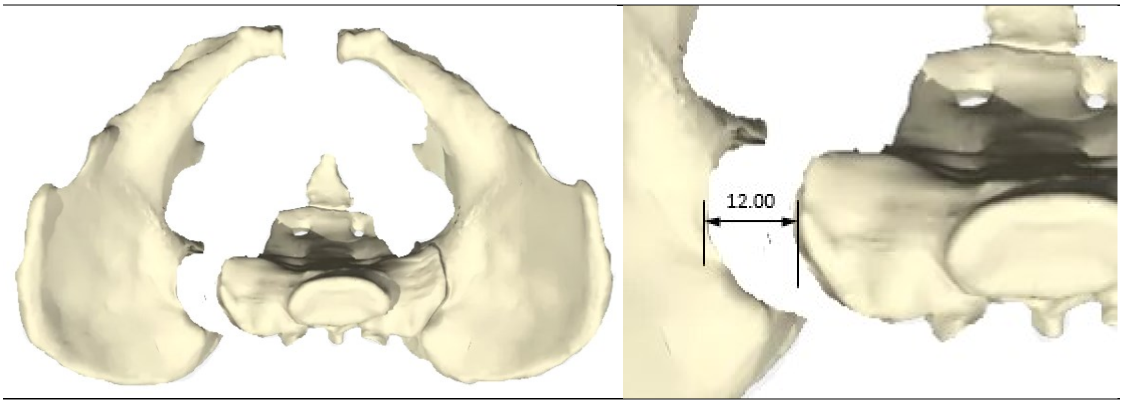
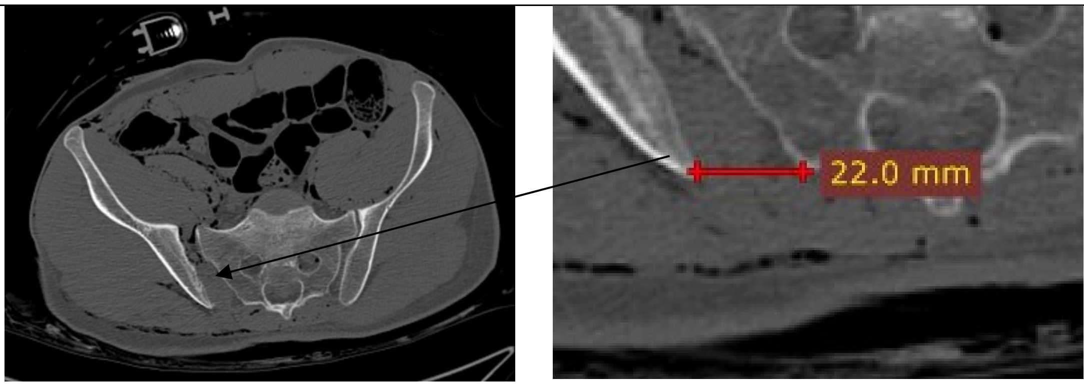


Figure 6.14: The measurement of lateral displacement of the hemipelvis (measured at the point of maximal diaplacement).



(a) **(b)**

Figure 6.15: Lateral Displacement of the SIJ at the maximal portion. (a) Lateral disruption of the iliac wing relative to the sacrum (b) Zoomed image of the measurement of the lateral seperation of the sacroiliac joint.

6.3.4 Pubic Symphysis

A similar technique was used to evaluate A-P, S-I and lateral separation of the PS, as demonstrated in the examples below.

Superior-Inferior Disruption of the PS

In PS S-I disruption, the measuring tool was used to measure the most superior part of the displaced PS, to the most superior part of the contralateral PS (Figure 6.16).

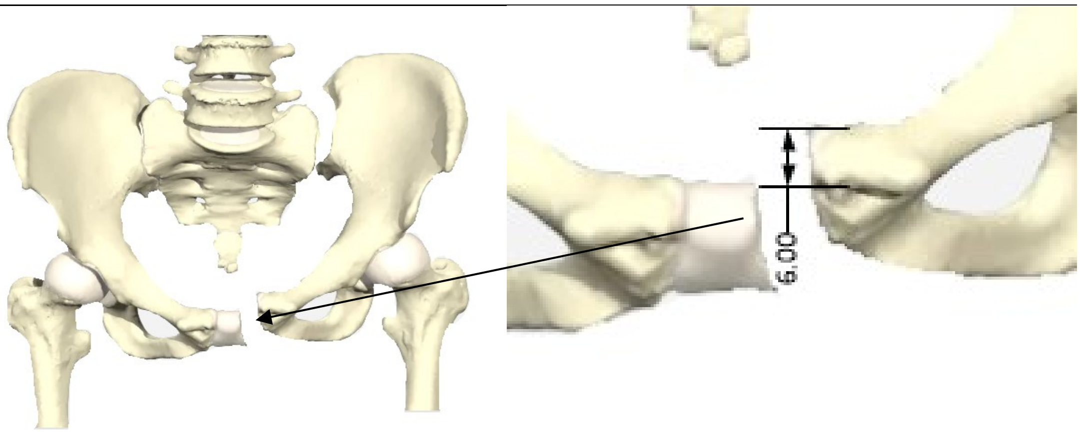
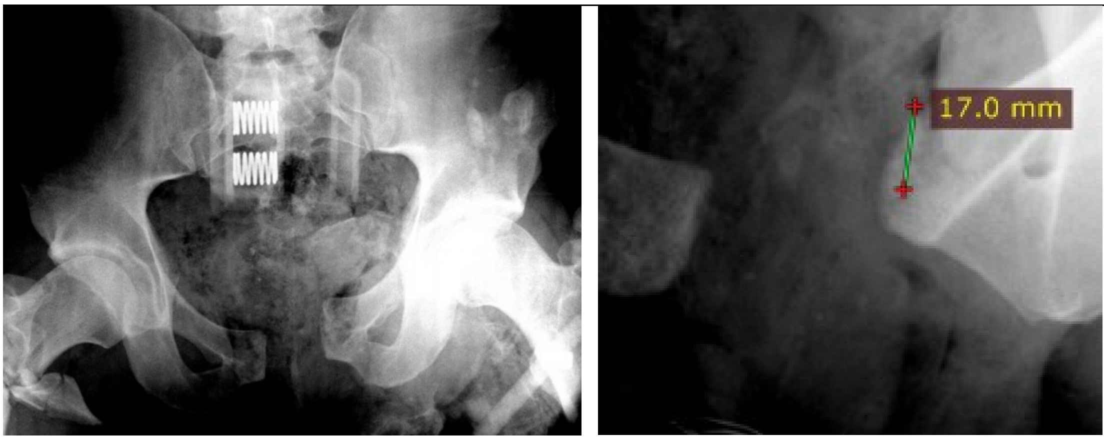


Figure 6.16: The measurement of superior-inferior displacement of the pubic symphysis.

S-I displacement of the PS was measured using either a coronal view on CT scans, or a plain film if the coronal view was not adequate. An example of this method is demonstrated below using a plain pelvic film (Figure 6.17).



(a) **(b)**

Figure 6.17: (a) Superior-inferior displacement of the pubic symphysis (b) measured at the most superior part of the disrupted pubic symphysis, to the most superior part of the contralateral joint.

Anterior Posterior Displacement of the Pubic Symphysis

A-P measurement was performed on axial CT scans, where the most anterior part of the disrupted PS was measured to the post anterior part of the contralateral side of the PS (Figure 6.18). An example of this method is demonstrated below (Figure 6.19).

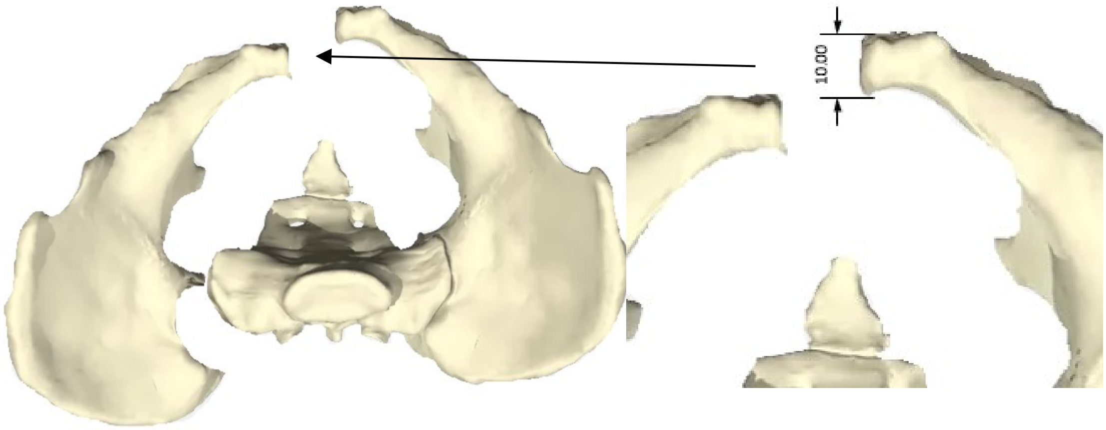
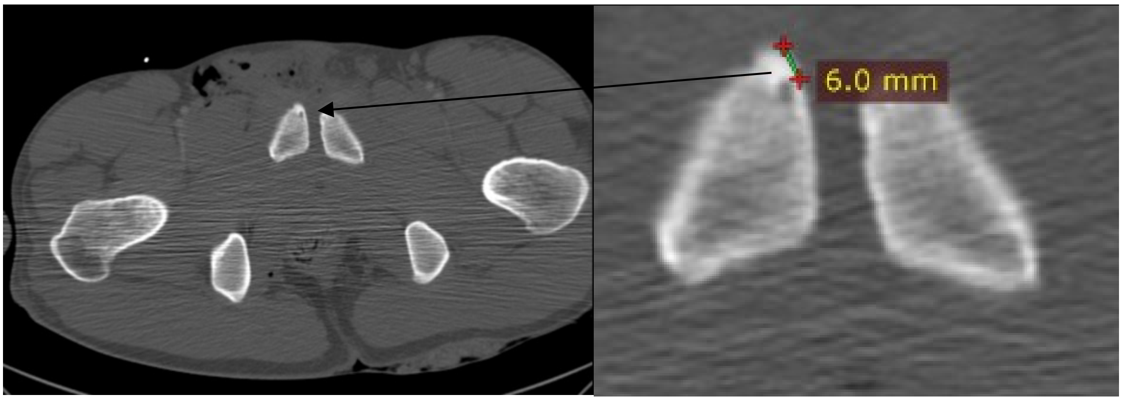


Figure 6.18: The measurement of anterior displacement of the hemipelvis



(a) **(b)**

Figure 6.19: (a) Anterior-posterior displacement of the pubic symphysis (b) measured from the most anterior point of the disrupted side of the pubic symphysis, to the most anterior part of the contralateral side of the joint.

Lateral

Lateral separation was measured at the greatest separation distance between the two sides of the PS, as demonstrated below (Figure 6.20). An example of this method in practice is presented below. (Figure 6.21).

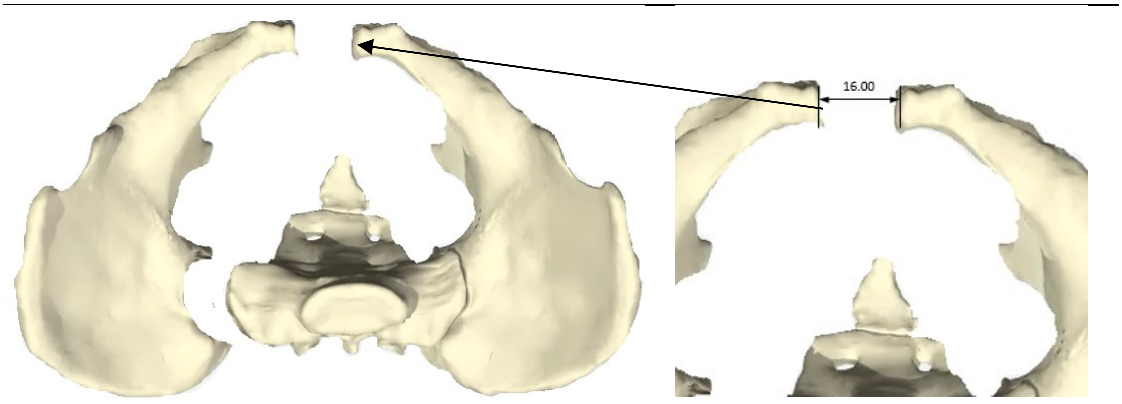
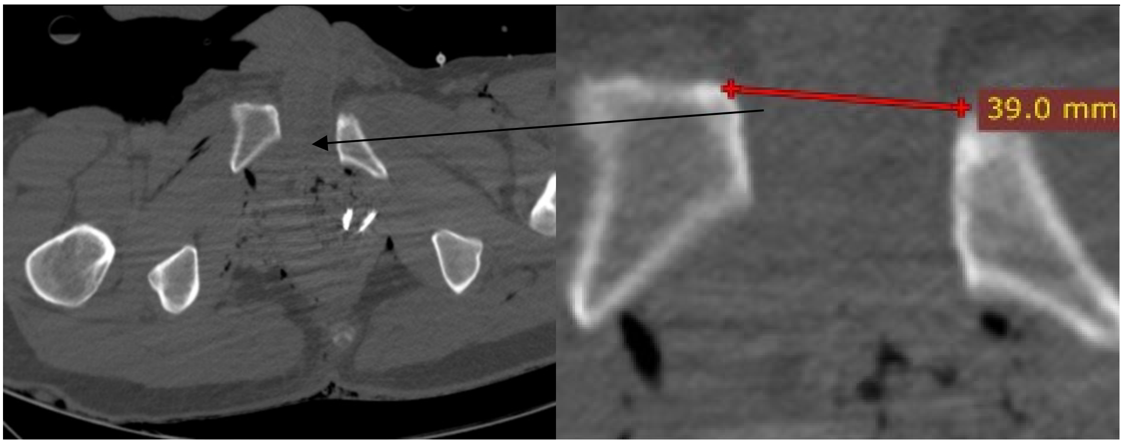


Figure 6.20: The measurement of lateral displacement of the hemipelvis.



(a) **(b)**

Figure 6.21: (a) Lateral displacement of the Pubic Symphysis and (b) measurement of the point of maximal displacement.

6.3.5 Data Collection

Casualty images from the database of 160 blast pelvic injures in this research cohort were sought, via the Royal Centre for Defence Radiology (RCDR), RCDM. A total of 31 (19%) of images were not available due to administrative and logistical regions described below. This left 129 (81%) of images available for analysis, via the PACS system at RCDM, and for PMCTs via the DCA in Radiology, Portsmouth (Figure 6.22). Casualties were only considered to have sufficient imaging if at least a CT scan was available, either performed in an injured casualty, or a post mortem CT, in order to obtain measurements in all planes. Included casualties were divided into mounted (n=23) and dismounted (n=104). One casualty in the dismounted cohort sustained a hemipelvectomy. This casualty was excluded due to the inability to perform measurements because of the missing hemipelvis.

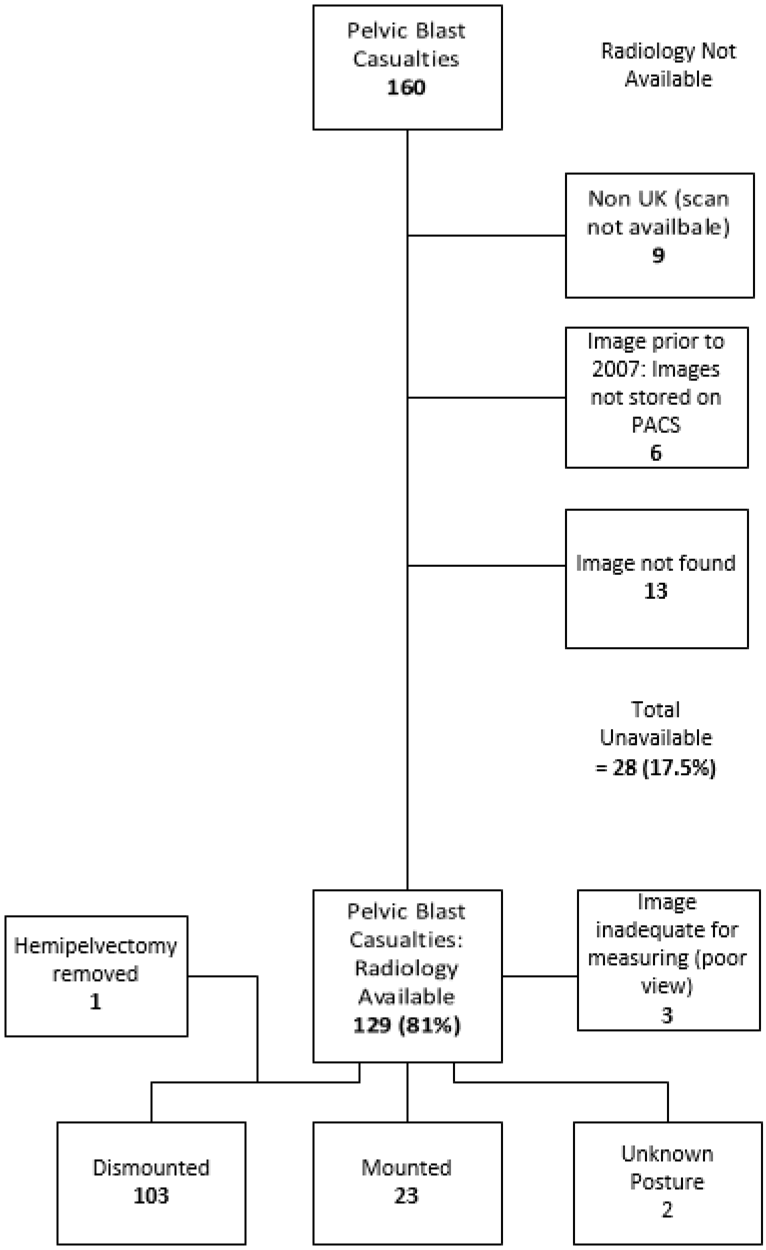


Figure 6.22: Image collection from blast pelvic casualties. Excluded casualties are stated. These were excluded due to scans not being available (reasons stipulated) or due to inadequate available views meaning accurate measurement was not possible.

6.4 Results

6.4.1 Data Overview: Sacroiliac Joint Disruption

The measurement data is shown in the tables and graphs below; pelvic disruption distances are presented in the three planes, both with and without a vascular injury. Positive numbers represent anterior and superior disruption, negative numbers inferior and posterior disruption.

Sacroiliac Joint Anterior-Posterior Disruption

The casualties with A-P disruption without and with vascular injury are presented in Table 6.1 and Table 6.2, respectively. Regardless of the level of disruption, the significance of disruption or no disruption and the presence of vascular injury in the A-P plane is $p = 0.0264$. The range of disruption is -3 to +4 mm in cases with no vascular injury, and -18 to +40 mm in cases with vascular injury.

Disruption distance (mm)	Frequency	%
-3	2	3
0	32	48.5
1	2	3
4	1	1.5
Total	37	100

Table 6.1: Sacroiliac joint anterior-posterior disruption distances in cases with no vascular injury. Positive numbers represent anterior disruption; negative numbers represent posterior disruption.

Disruption distance (mm)	Frequency	%
-18	1	1.5
-14	1	1.5
-10	1	1.5
-7	1	1.5
-5	1	1.5
-4	3	4.5
-3	1	1.5
-2	3	4.5
-1	1	1.5
0	42	63.6
2	1	1.5
3	2	3
4	2	3
7	2	3
11	1	1.5
12	1	1.5
17	1	1.5
40	1	1.5
Total	66	100

Table 6.2: Sacroiliac Joint Anterior-posterior disruption distances in cases with vascular injury. Positive numbers represent anterior disruption; negative numbers represent posterior disruption.

Sacroiliac Joint Superior Inferior Disruption

The casualties with S-I disruption without and with vascular injury are presented in Table 6.3 and Table 6.4, respectively. Regardless of the level of disruption, the significance of disruption or no disruption and the presence of vascular injury in the A-P plane is $p = 0.0377$. The range of disruption is -5 to +10 mm in cases with no vascular injury, and -33 to +15 mm in cases with vascular injury.

Disruption distance (mm)	Frequency	%
-5	1	1.5
0	34	51.5
4	1	1.5
10	1	1.5
Total	37	100

Table 6.3: Sacroiliac Joint Superior-Inferior disruption distances in cases with no vascular injury.

Disruption distance (mm)	Frequency	%
-33	1	1.5
-13	1	1.5
-8	2	3
-5	1	1.5
-2	2	3
-1	1	1.5
0	49	74.2
2	2	3
4	1	1.5
8	2	3
11	1	1.5
12	1	1.5
13	1	1.5
16	1	1.5
Total	66	100

Table 6.4: Sacroiliac Joint Superior-Inferior disruption distances in cases with vascular injury.

SIJ Lateral Displacement

The casualties with lateral disruption without and with vascular injury are presented in Table 6.5 and Table 6.6, respectively. Regardless of the level of disruption, the significance of disruption or no disruption and the presence of vascular injury in the A-P plane is $p = 0.0002$. The range of disruption is 0 to 19 mm in cases with no vascular injury, and 0 to 30 mm in cases with vascular injury.

Disruption distance (mm)	Frequency	%
0	17	25.8
2	1	1.5
3	4	6.1
4	4	6.1
5	4	6.1
7	1	1.5
8	4	6.1
11	1	1.5
19	1	1.5
Total	37	100

Table 6.5: Sacroiliac Joint Lateral disruption distances in cases with no vascular injury.

Disruption distance (mm)	Frequency	%
0	8	12.1
1	1	1.5
2	3	4.5
3	7	10.6
4	3	4.5
5	11	16.7
6	6	9.1
7	3	4.5
8	3	4.5
10	4	6.1
11	1	1.5
12	3	4.5
13	1	1.5
15	1	1.5
16	4	6.1
18	4	6.1
20	2	3
30	1	1.5
Total	66	100

Table 6.6: Sacroiliac Joint Lateral disruption distances in cases with vascular injury.

6.4.2 Data Overview: PS Disruption

Pubic Symphysis Anterior-Posterior

The casualties with A-P disruption without and with vascular injury are presented in (Table 6.7) and Table 6.8 respectively. Regardless of the level of disruption, the significance of disruption or no disruption and the presence of vascular injury in the AP plane is $p = 0.0237$. The range of disruption is 0 to 27 mm in cases with no vascular injury, and 0 to 36 mm in cases with vascular injury.

Disruption distance (mm)	Frequency	%
0	23	34.8
1	1	1.5
3	5	7.6
4	2	3.0
8	2	3.0
10	1	1.5
11	1	1.5
17	1	1.5
27	1	1.5
Total	37	100

Table 6.7: Pubic Symphysis anterior-posterior disruption distances in cases with no vascular injury.

Disruption distance (mm)	Frequency	%
0	25	37.9
1	2	3
2	6	9
3	4	6
4	6	9
5	3	4.5
6	2	3
7	3	4.5
8	1	1.5
10	5	7.6
11	1	1.5
12	1	1.5
13	1	1.5
14	1	1.5
18	1	1.5
20	1	1.5
23	1	1.5
26	1	1.5
36	1	1.5
Total	66	100

Table 6.8: Pubic Symphysis anterior-posterior disruption distances in cases with vascular injury.

Pubic Symphysis Superior-Inferior

The casualties with S-I disruption without and with vascular injury are presented in Table 6.9 and, Table 6.10 respectively. Regardless of the level of disruption, the significance of disruption or no disruption and the presence of vascular injury in the A-P plane is $p = 0.0004$. The range of disruption is 0 to 17 mm in cases with no vascular injury, and 0 to 48 mm in cases with vascular injury.

Disruption distance (mm)	Frequency	%
0	22	33.3
1	2	3
3	5	7.6
4	2	3
5	2	3
8	1	1.5
10	1	1.5
11	1	1.5
17	1	1.5
Total	37	100

Table 6.9: PS Superior-inferior distances in cases with no vascular injury.

Disruption distance (mm)	Frequency	%
0	20	30.3
2	1	1.5
3	5	7.6
4	4	6.1
5	7	10.6
6	4	6.1
7	6	9.1
8	3	4.5
10	3	1.5
12	1	1.5
13	2	3
14	3	4.5
19	1	1.5
20	1	1.5
26	2	3
34	1	1.5
36	1	1.5
48	1	1.5
Total	66	100

Table 6.10: Pubic Symphysis superior-inferior disruption distances in cases with vascular injury.

Pubic Symphysis Lateral Disruption

The casualties with lateral disruption without and with vascular injury are presented in Table 6.11 and Table 6.12 respectively. Regardless of the level of disruption, the significance of disruption or no disruption and the presence of vascular injury in the AP plane is $p = 0.0075$. The range of disruption is 0 to 67 mm in cases with no vascular injury, and 0 to 166 mm in cases with vascular injury.

Disruption distance (mm)	Frequency	%
0	15	22.7
2	1	1.5
4	2	3
5	1	1.5
6	2	3
8	2	3
13	1	1.5
14	2	3
15	1	1.5
16	1	1.5
17	1	1.5
19	1	1.5
24	1	1.5
28	1	1.5
29	1	1.5
37	1	1.5
50	2	3
67	1	1.5
Total	37	100

Table 6.11: Pubic Symphysis Lateral distances in cases with no vascular injury.

Disruption distance (mm)	Frequency	%
0	10	15.2
2	2	3
3	1	1.5
4	2	3
5	4	6.1
6	4	6.1
7	2	3
8	1	1.5
10	2	3
11	2	3
12	4	6.1
14	1	1.5
16	1	1.5
18	2	3
19	1	1.5
20	2	3
22	1	1.5
25	2	3
27	1	1.5
28	2	3
36	1	1.5
38	1	1.5
40	2	3
42	1	1.5
44	3	4.5
45	1	1.5
47	1	1.5
50	2	3
70	1	1.5
100	1	1.5
166	1	1.5
Total	66	100

Table 6.12: Pubic Symphysis lateral disruption distances in cases with vascular injury.

Following the assessment of distances of disruption and the presence or absence of vascular injury, the ability of these displacements to predict vascular injury was assessed using statistical analysis in the following section.

6.4.3 Vascular Injury Prediction

The purpose of this statistical analysis was to ascertain whether a certain direction or magnitude of displacement could predict the likelihood of the presence or absence of vascular injury, which we know from the analysis in this research often leads to fatalities. If bony disruption can predict vascular injury, then this research can make a recommendation regarding the amount of reinforcement, and in which direction/s, that is required of PPE designed to help mitigate pelvic opening. Therefore, for this type of analysis, area under receiver operator characteristic (AUROC) curves were used to identify which direction of disruption is most associated with vascular injury, and by how much.

AUROC curves are a statistical tool that plot the chances of a true positive value (sensitivity) against the chance of a true negative value (specificity). These values create curves which are used to select a cut-off point to determine the most likely point in which an outcome can be predicted. This is an evaluation that is chosen by the operator, based on the desired specificity and sensitivity of the prediction required (i.e. for some analyses, picking up every value might be important (sensitivity) whereas in other analyses, avoiding false negative values might be important (specificity)). Usually a compromise between the two is selected. In this analysis, the sensitivity and specificity of the ability of the level of disruption to predict vascular injury was analysed, to assess whether the chance of a vascular injury could be predicted based on how much disruption had occurred in a particular plane. An AUROC value of 0.8 is generally considered to be sufficiently reliable at detecting outcomes (Hanley and McNeil 1982).

The median and range were used to summarise continuous variables. The Mann-Whitney test was used to compare continuous variables such as SIJ anterior or posterior displacement by whether the subject had a vascular injury or not, with significance set at p<0.05. AUROC curves were subsequently produced for each displacement measure showing differences between subjects that have or don't have vascular injury. Stata version 13 was used for analysis and was performed in consultation with Joseph Eliahoo, a senior statistician at Imperial College London.

The summary of data within the groups of cases with vascular injury and the control group, with the median and range and differences (p<0.05) between the two, are demonstrated in the table below. This demonstrated significant differences in magnitude of disruption between those with vascular injury, and those without (Table 6.13).

Direction and amount of pelvic disruption (mm)	Vascular Injury Median(Range)	Controls Median(Range)	p- value*
SI Joint Anterior/Posterior Disruption	0 (0-40)	0 (0-4)	0.006
SI Joint Superior/Inferior Disruption	0 (0-33)	0 (0-10)	0.03
SI Joint Lateral Disruption	5.5 (0-30)	3 (0-19)	0.0001
PS Anterior/Posterior Disruption	2.5 (0-36)	0 (0-27)	0.024
PS Superior/Inferior Disruption	5 (0-48)	0 (0-17)	0.0004
PS Lateral Disruption	12 (0-100)	5 (0-67)	0.022

Table 6.13: Data Summary of disruptions in those with vascular injury, and controls (pelvic disruption with no vascular injury). *Mann Whitney tests were used to establish the p-values, with significance set at 0.05.

Sacroiliac Joint Anterior-Posterior Displacement

Disruption in the A-P plane is significantly higher in those casualties with a vascular injury (p=0.006), meaning the larger the disruption in the A-P plane, the higher the likelihood of vascular injury. However, the median value is the same (0mm) in both those with vascular injury and control cases. In addition, the AUROC curve of 0.6292

(Figure 6.23) suggests that the distance in this plane is not a reliable indicator of vascular injury (values of less than 0.8 are generally not considered reliable values).

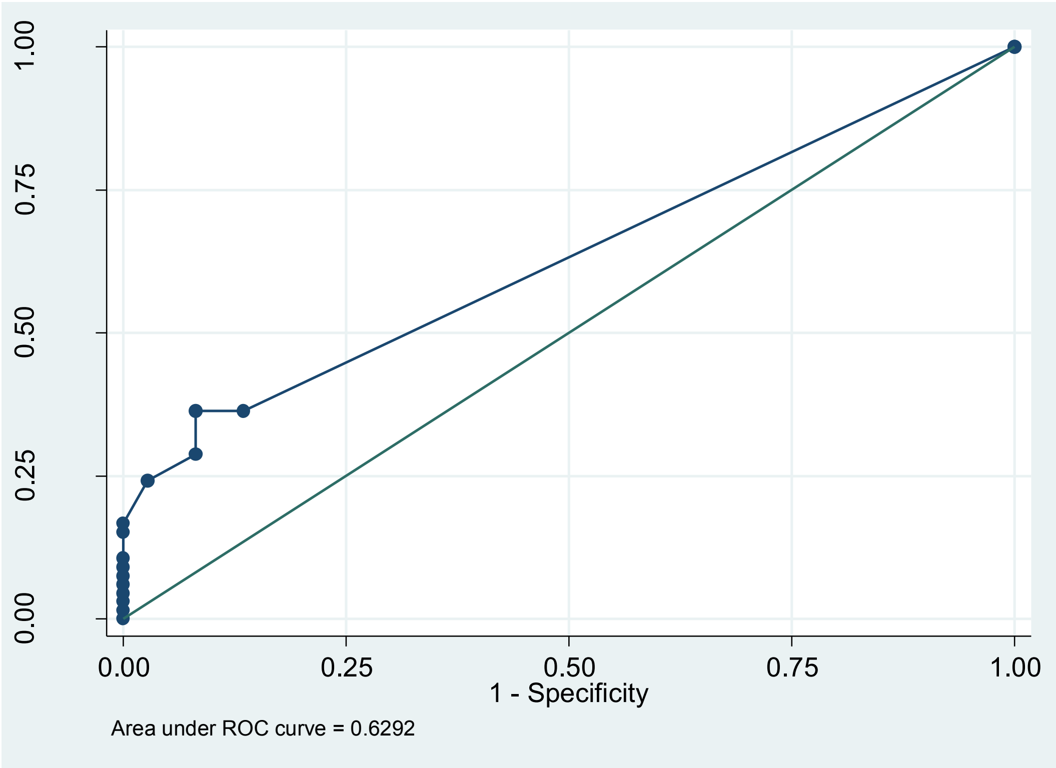


Figure 6.23: AUROC Curve for anterior-posterior displacement of the SI Joints.

SIJ Superior-inferior displacement

S-I disruption appears to be less significantly associated with vascular injury than A-P (p=0.03) although still significant. The AUROC curve for this plane shows a level of 0.5893 (Figure 6.24) which, again, does not provide reliable sensitivity or specificity levels for vascular injury. Therefore, although larger values of superior inferior SIJ disruption are associated with bleeding, disruption in the superior-inferior plane is not a reliable indicator for predicting vascular injury.

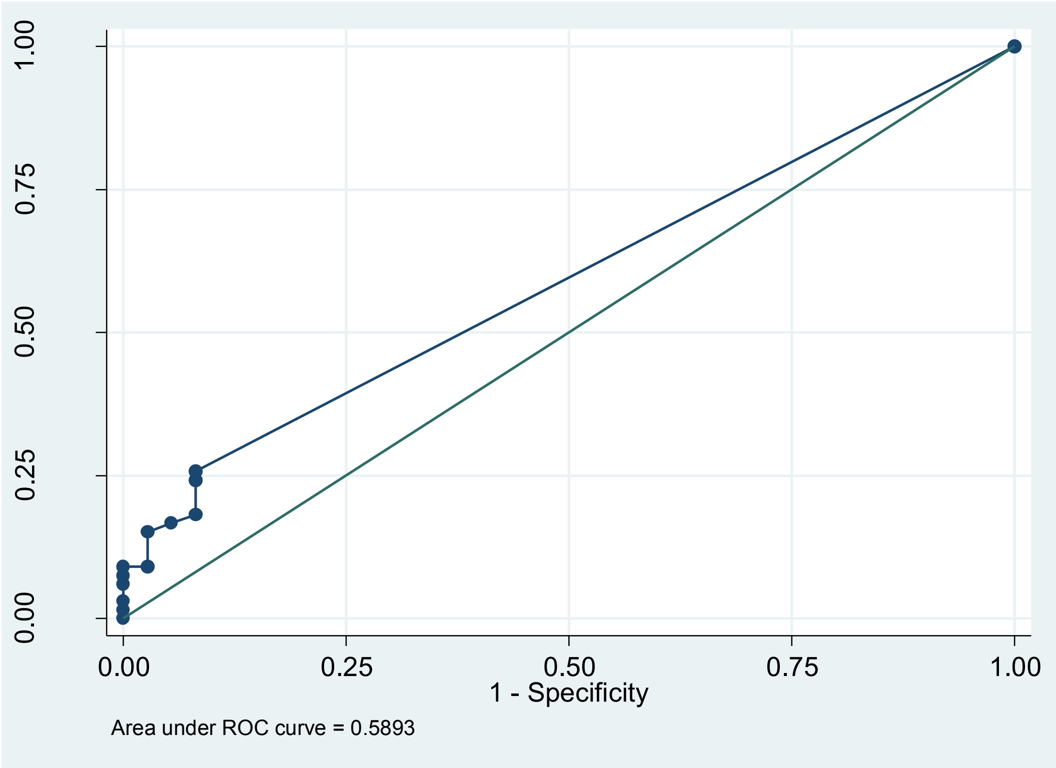


Figure 6.24: AUROC Curve for superior-inferior displacement of the SI Joints.

SIJ Lateral displacement

Lateral displacement of the SIJs is most significantly associated with vascular injury (p=0.0001), with higher median vales in those with vascular injury (5.5mm) versus those without (3mm), and ranges demonstrating higher maximum values in those with vessel rupture. The AUROC curve is also the most convincing of the analysis at 0.7299 (Figure 6.25). Lateral movement of the SIJs is therefore the most strongly associated with vessel injury, and has the highest sensitivity and specificity of predicting vascular injury.

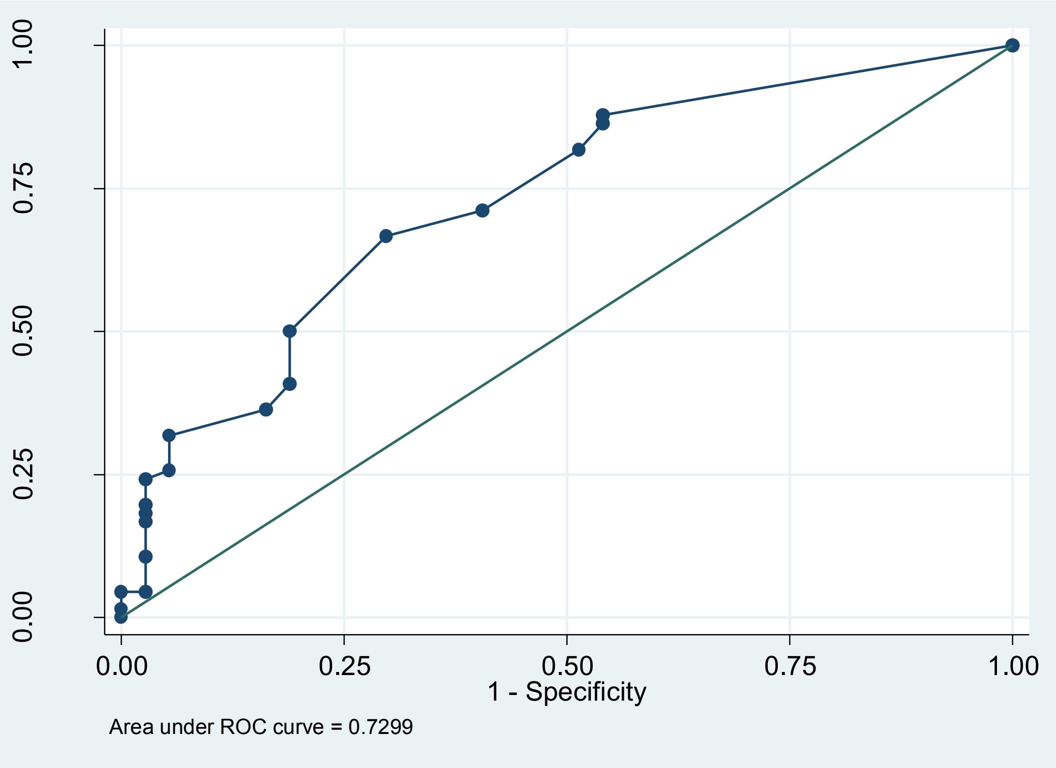


Figure 6.25: AUROC Curve for lateral displacement of the SI Joints.

PS Anterior-Posterior Disruption

A-P disruption of the PS is positively associated with vascular injury, (p=0.024), with higher medians in those with vascular injury (2.5 versus 0 mm) and a higher maximal value. The AUROC value is 0.63 (Figure 6.26).

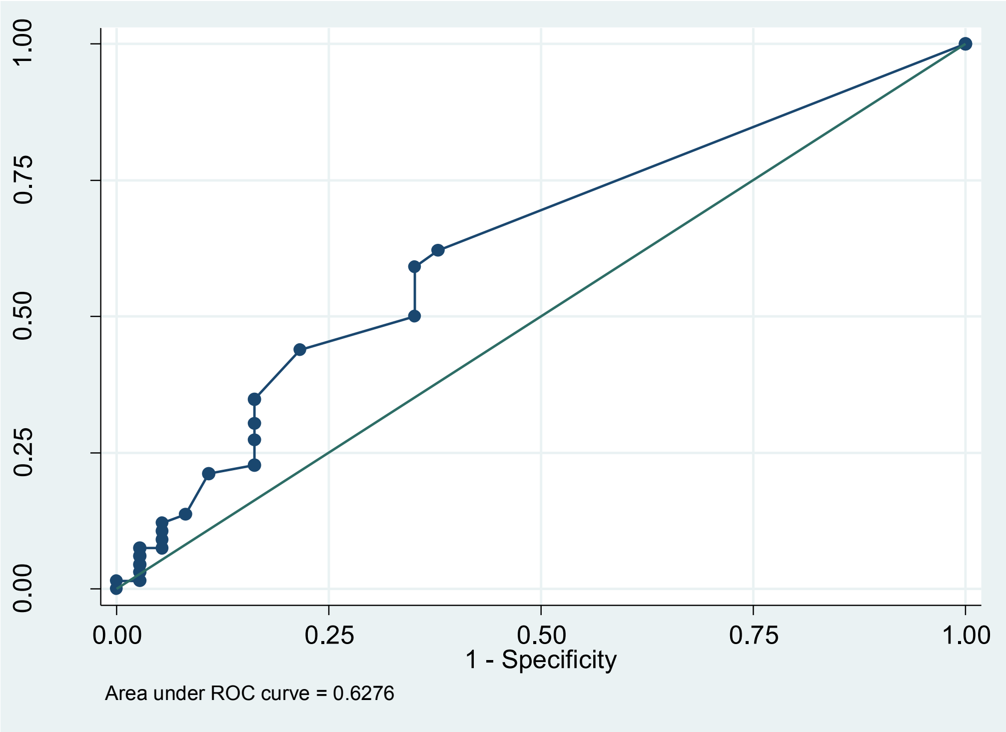


Figure 6.26: AUROC Curve for anterior-posteior disruption of the PS.

The A-P disruption of the PS is important, however, there are some 0mm values that do not sustain vascular injury. The AUROC value may be able to predict the presence of vascular injury with this measurement of PS disruption.

PS Superior-inferior disruption

S-I PS opening is the most significantly associated with vascular injury, with p=0.0004. Median values are again higher in vascular injury (5mm versus 0mm for those without disruption in this plane) and the maximal value is higher in those with vascular injury. The AUROC curve value is 0.7025 (Figure 6.27), a fairly reliable predictor for the presence of vascular injury in this plane.

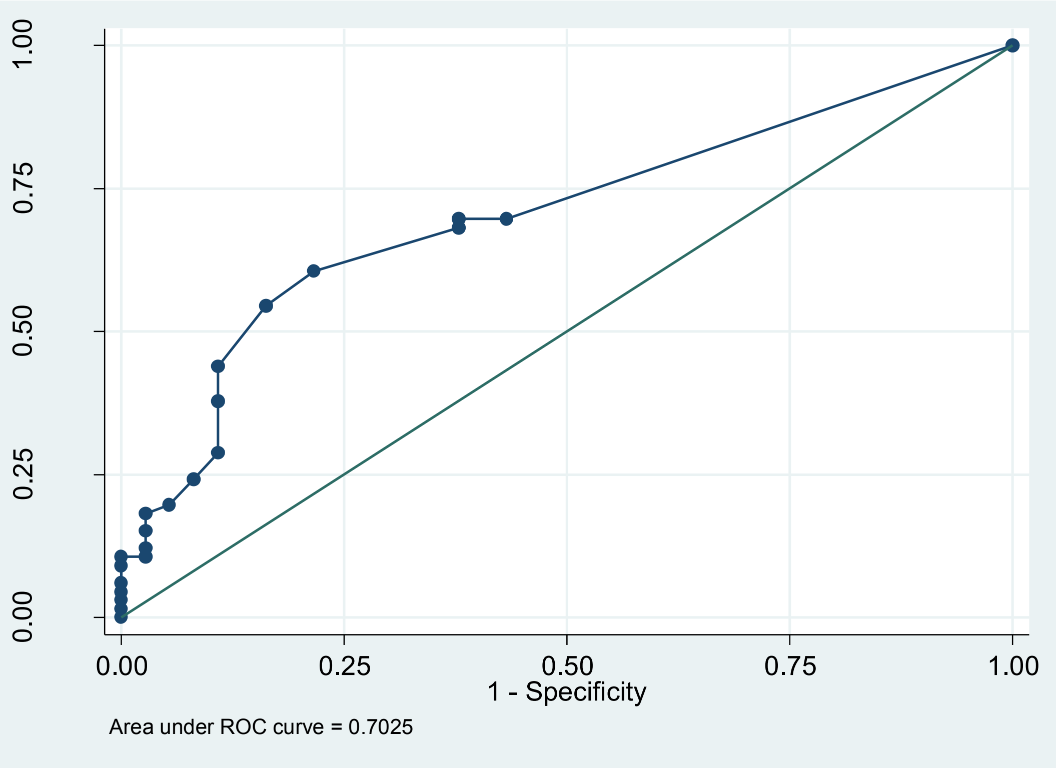


Figure 6.27: AUROC Curve for superior-inferior disruption of the PS.

S-I disruption could be important in terms of preventing vascular injury, however, for a predictive tool, this plane of disruption is not convincingly sensitive or specific enough for determining the presence of vascular injury.

PS Lateral Separation

This plane of disruption of the PS is significantly associated with vascular injury (p=0.022) and has the greatest difference in median values (12mm for those with vascular injury versus 5mm in those without). The AUROC value here is the weakest of the dataset at 0.6358 (Figure 6.28), meaning lateral separation of the PS is the least reliable in predicting vascular injury within the pelvis.

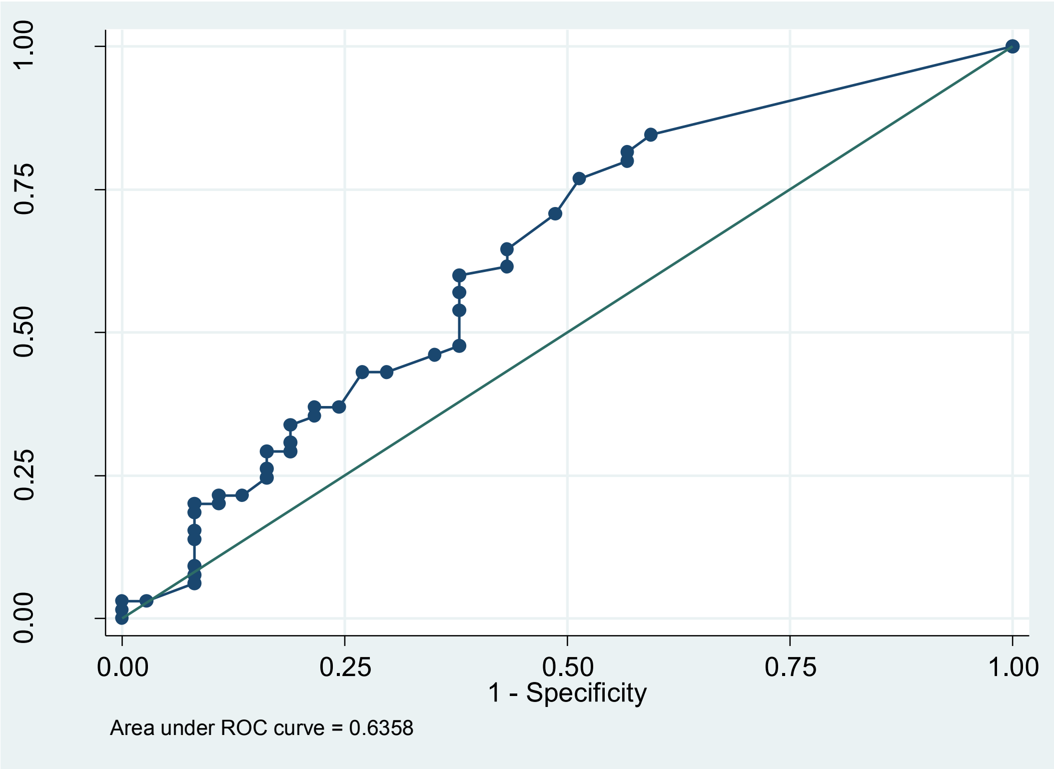


Figure 6.28: AUROC Curve for lateral disruption of the PS.

6.5 Discussion

In the initial analysis of the data in this section, with regards to the SIJs, there is variation in disruption distances in both those cases with and without vascular injury. However, there is a greater range of distances present in those with vessel injury, and generally higher levels of disruption in those casualties with vascular injury. Of the three planes examined in SIJ displacement, the lateral direction is most significantly associated with the presence of a vascular injury (p = 0.0002). In A-P and S-I, significance is p=0.0264 and p=0.0377 respectively, between disruption in these planes and the presence of vascular injury, which is significant, but less so than lateral directions. In addition, in these two planes, there are multiple cases, both with and without vascular injury, that are not disrupted in these planes (0mm of disruption), meaning vascular injury can occur when separation in these planes has not occurred.

This suggests that widening in A-P and S-I planes is not a requirement for vascular injury to occur.

In PS injury, as with the SIJs, there is a greater range of disruptions in those with vascular injury in all planes. In this joint, S-I opening shows the most significant differences between joint widening and vascular injury (p=0.004), followed by lateral disruption (p=0.0075) and A-P (p=0.0237). It was expected that opening in the lateral direction, if the most important in the SIJ, would also be important in the PS. However, due to the mechanical instability of the pelvis when the PS has disrupted, it may be that the PS shows variability in position due to ring laxity, and measurements are reflective of the final resting positions of the pelvis, rather than the maximal opening that has occurred during injury. This may be the case for all measurement data in this series.

With regards to the potential of the disruption levels to predict the presence of vascular injury in the statistical analysis using the AUROC method, neither A-P nor S-I planes provide enough sensitivity or specificity to be able to predict vessel injury. Lateral disruption of the SIJs however, is the most predictive of vessel injury, and may be sensitive enough to predict its likelihood. In PS separation, S-I separation is the most sensitive at detecting the presence of vascular injury at AUROC of 0.7. A-P does not offer enough predictive ability to suggest vessel injury, and lateral separation is the least reliable in predicting vessel injury, potentially due to variability as previously stated, in final resting positions.

This was a retrospective study using films previously taken in a clinical scenario, in which the films were taken for the purposes of management of injuries, and not for the purposes of detailed biomechanical analysis. Therefore there will have been variations in scan orientation. As the CT scans were not taken specifically for this study, there may be slight variations as to the views, with some rotation of scans that may give some variation as to the measurements, particularly as many of these scans were taken in an emergency. The main limitation of this measurement technique, is that these measurements asses the bony disruption at a fixed, final position after the injurious event; there is no method with the available data to assess the extent of the dynamic disruption at the time of injury. In addition, the combination of planes of disruption could also be important, combinations of anterior and lateral movement of the pelvis for example. This information is key however, in looking at specific planes of movement, and this alone can start to inform the target for preventative techniques.

There was a finite number of pelvises that have been exposed to blast available for review, so there was a specific number available for analysis. Therefore no power study could be performed to ensure statistical reliability as there is no option to expand the dataset. There is the prospect however, of repeating this study if more data were to become available in the future.

6.6 Conclusion

This study is the first of its kind to present data on joint separation and correlation with vascular injury using a statistical analysis. This gives important information concerning the direction and magnitude of bony separation and its correlation with disruption to blood vessels. It points to lateral separation at the SIJs, and S-I disruption at the PS demonstrating a trend towards predicting vessel injury. In the ability to predict vascular injury, SIJ lateral separation and S-I disruption were also the most sensitive in predicting the presence of vessel injury. The two main limitations of this measurement system for pelvic fractures is 1) the uncertainty as to how much larger – if at all – the disruption at the time of injury had been compared to the one measure on a CT scan post injury, and 2) this study only combines pelvic disruption in three planes. In order to address this the following presents a novel finite element model that simulates extensive pelvic disruption at multiple planes and includes the main blood vessels. Combining the data here with the simulation results demonstrates a correlation between pelvic disruption and location of main vessel injury may be estimated. This information may suggest the direction and magnitude of reinforcement required to resist pelvic joint separation, which is key to informing protective techniques.

CHAPTER 7

A PHYSICAL MODEL OF DISMOUNTED BLAST PELVIC INJURY

Physical models have been utilised in blast research to simulate explosive injuries. Although injury patterns can be analysed post incident, as performed in chapters 3 and 5, and quantified in chapter 6, dynamic deformation is difficult to assess, and therefore physical experiments can assist in the understanding of tissue response during the course of the blast. The clinical data and pelvic measurements presented earlier enabled theories of the mechanism of PI to be hypothesised, and these can be tested against lab based physical experiments. This chapter summarises methods of physical testing previously used in blast, and describes a new experimental technique, aimed to replicate blast to the pelvis in a standing posture, to gain a further understanding of pelvic disruption during blast.

7.1 Introduction

Impact injuries to the human body are caused by deformation of tissues beyond their recoverable limit, leading to a disruption of normal structure and/or function (Viano, King, et al. 1989). The field of impact biomechanics concerns mechanisms of injury, mechanical responses, and human tolerance to injury, or injury risk. This data is most often gained by controlled testing methods whereby an injury scenario is replicated as closely as possible, and monitoring techniques assess impact characteristics and the responses of subjects. These analyses often culminate in producing a risk of injury, usually in the form of injury risk curves (King 2000). Mechanisms of injury are hypothesised and tested using appropriate known or novel testing strategies. In the field of trauma biomechanics, a variety of mechanisms have been reproduced, such as automobile incidents, falls, and more recently, blast injury. These methods apply loading in different directions and magnitudes depending on what is being replicated. Early experiments focussed on static application of force (Hiroshi Yamada 1971), however, as understanding has progressed, not just the force is deemed an important factor in determining injury, but the speed in which it is applied. This is due to the viscoelasticity (characteristics of both resistance and elasticity) of human tissues (Lau and Viano 1981).

When considering penetrating injuries, physical disruption to body areas occurs when sharp objects, or projectiles, breach and enter the body. As force is concentrated over a small area, and the speed at which the device moves is such that the body cannot deform and absorb the load (Viano, King, et al. 1989). Therefore direct injury occurs to surrounding tissues. In blunt injuries, there is deformation of tissues which is measured in terms of strain; a change in dimension due to an applied load divided by the original dimensions of the structure. There are three types of strain: tensile, shear, and compressive, which can all cause fractures of bony structures, and soft tissue injuries (Fung and Skalak 1981).

Replicating injury is a complicated process due to the number of variables that need to be considered. The velocity, mass, and direction of loading, as well as the rate and duration must be considered, as must specimen orientation and appropriate fixation (boundary conditions). In addition, specimen characteristics such as age, sex, physical condition, disease, and surrounding environment such as seating and restraints if applicable, must be acknowledged. However, considering that trauma is a leading cause of morbidity and mortality in the UK, particularly in the young (Pearson, Henning, and Woods 2017), there are tremendous gains to be made in terms of understanding the mechanism of trauma and refining treatment and prevention that can save lives.

Recreating the loading during an explosive incident is very important in assessing the effects of blast on structures (e.g. vehicles or infrastructure) and personnel, for both understanding injury outcomes following blast exposure, and developing mitigation technologies, in which relatively simple interventions could save lives. The complex explosive effects are often recreated when blast is compartmentalised into its different clinical effects of primary, secondary and tertiary, as mitigation may differ for protecting against these three categories of blast. Experimental techniques for reproducing blast loading can take various forms, with advantages and disadvantages to each experimental set up. Also, in addition to cadaveric tests, there is a variety of testing surrogates that can be used to map outcomes of blast trauma on the body, again, each set up has inherent strengths and weaknesses.

7.2 Replicating the Blast Environment

7.2.1 Replicating Primary Blast Injury

Primary blast injury (Chapter 2.2.4) can be recreated using tests of various scales depending on the test subject. In free field blast tests, aimed at a larger scale targets, such as vehicles or infrastructure, explosives are used in an open space, generating a blast wave to assess its characteristics and, for example, the effects of surrounding infrastructure on its mechanism of action (Houlston, Slater, and Ritzel 1991). These tests are more useful in determining mortality thresholds than injury specifics, as it is difficult for these events to be tightly controlled and instrumented due to the destructive nature of the tests (Risling and Davidsson 2012) (Figure 7.1a). Additional difficulties with such experiments are cost, and space requirements.

On a smaller scale, for example for small animal testing, shock tubes are pieces of apparatus designed to administer pressure waves (Chapter 2.2.2) of a desired intensity to a specimen (Nguyen, Wilgeroth, and Proud 2014) (Figure 7.1b). This technique uses chambers separated with diaphragms to control the pressure to a desired intensity. On rupture of the diaphragm at a predetermined point the pressure is released and travels along the second chamber, thus applying a pressure wave as a simulation of a primary blast wave (Sundaramurthy et al. 2012). It is important to ensure that the specimen does not impact the tube walls as the blast is applied, to avoid a tertiary blast effect (Cernak 2005).

In order to ascertain the effects on a cellular level, a Split Hopkinson Bar (Figure 7.1c) is employed, which uses systems applying compression forces to cellular specimens. This is important when evaluating the effects on different biological cell types. This method has been utilised particularly in the assessment of brain cell damage due to primary blast (Pervin and Chen 2009), but has also been used to characterise the behaviour of muscle cells (Van Sligtenhorst, Cronin, and Wayne Brodland 2006), skin, (Shergold, Fleck, and Radford 2006) adipose tissue (Comley and Fleck 2012) and organs (Pervin, Chen, and Weerasooriya 2011). These cells can be placed in suspension, adhered to a surface, or embedded in alginate materials (Bo et al. 2011; Chang Yan, Nair, and Sun 2010; Nienaber et al. 2011). The Split Hopkinson Bar utilises a pressure chamber in order to fire a projectile into the incident bar leading to a pressure wave onto the prepared specimen. This aims to simulate the primary blast wave in cells.

(a) (b) (c)

Figure 7.1: (a) A free field blast test (b) shock tube, and (c) Split Hopkinson bar.

7.2.2 Replicating Secondary Blast Injury

Secondary blast fragmentation (Chapter 2.2.5) can penetrate all body tissues, and cause significant destruction, both from impregnated projectiles, fragmentation of the missile case, and surrounding environment (Covey 2002). The potential for fragments of different material properties, masses and speeds to penetrate human tissue has not yet been extensively modelled physically (Williams et al. 2005). Older models have focussed on the use of live animal tests, and are mainly ballistic methods to replicate gunshot type injuries rather than focussing on blast fragmentation. (Carey et al. 1989; Suneson, Hansson, and Seeman 1987). However, there are some new capabilities emerging, and further knowledge on secondary blast injury is imminent, such as results from the use of gas guns to propel projectiles onto a specimen using compressed air (Nguyen et al. 2017).

7.2.3 Replicating Tertiary Blast Injury

Tertiary blast (Chapter 2.2.6), occurs when solid objects cause impact due to blast, and transmit forces to anything in contact with them. Tertiary blast can refer to buildings or infrastructure, but within vehicles is perhaps more prolific, due to the expectation of combat vehicles to encounter explosions. The injuries caused by blast within vehicles can be attributed predominantly to the effects of this tertiary blast (Ramasamy, Hill, Phillip, et al. 2011), in which detonation of an IED beneath a vehicle causes deformation of the floor. This can lead to axial loading of personnel in contact with either vehicle floors or seats. Great improvements in safety can be employed following adaptation of vehicles likely to encounter blast (A Ramasamy et al. 2009), and appropriate testing mechanisms allow these to be further understood and developed. The loading seen in underbody blast is dependent on a variety of factors: charge size and type of explosion, soil characteristics, vehicle design, and the position of the individual within the vehicle. It is therefore important for there to be a variety of platforms available for testing solid blast.

Drop Rigs

A drop rig is an experimental set up by which a mass is dropped in a controlled manner onto a sample to assess the dynamic response (Figure 7.2). The mass and drop height can be varied to produce a desired load. Loads are commonly recorded using load cells within the experimental set up, and the falling mass is often fitted with a transducer to assess velocities. Results can be assessed by evaluating clinical data on wounding patterns achieved by scanning tested specimens, and correlating these injuries to specific loads applied over time (Yoganandan, Pintar, et al. 2015). Deformation can also be assessed in specific regions of interest using strain gauges or accelerometers attached to specific points within specimens, physical markers measured with high speed video, or acoustic sensors (Arun et al. 2014). These drop tower devices provide a repeatable, reliable testing mechanism in which to test tertiary blast. Drop towers have also been utilised to simulate solid impacts in aviation incidents in the spine (Yoganandan, Stemper, et al. 2015) and brain (in a small animal model) (Stemper et al. 2016).

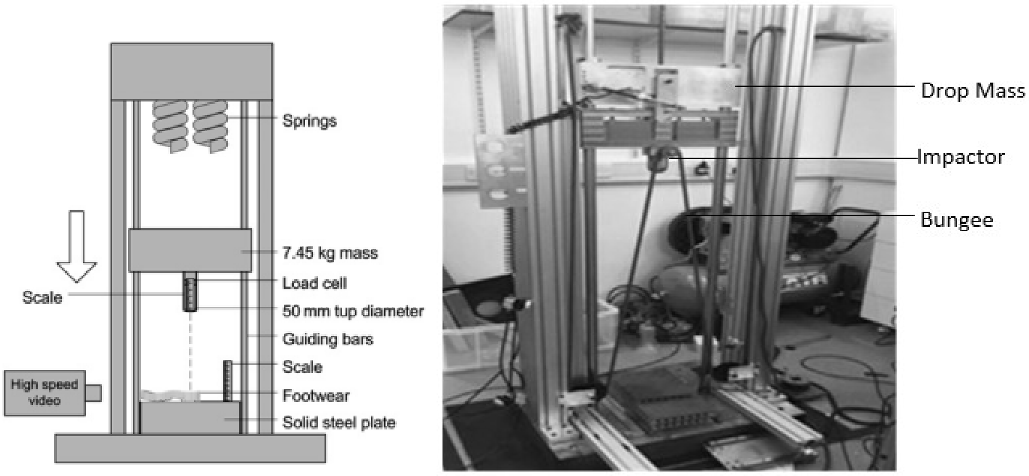


Figure 7.2: (a) example of a drop rig set up in schematic form (Newell et al. 2012) and (b) a photograph of a design, with added bungees placed to increase the velocity of the falling mass.

Traumatic Injury Simulators

Traumatic injury simulators replicate the loading transmitted to vehicle occupants during an under-vehicle explosion, a common occurrence in the recent conflicts (Danelson et al. 2015a). They usually involve a large mass which is forcibly accelerated into specimens at predetermined speeds, and therefore applies specified desired loads. There are various examples of traumatic injury simulators which have been developed worldwide. Initially these primarily focussed on lower limb injury analysis (Masouros et al. 2013; Mckay 2010) (Figure 7.3) however, more recently, traumatic injury simulators have been developed to undertake whole body testing (Bailey et al. 2015; Yoganandan, Pintar, et al. 2015). The advantages and disadvantages of component versus whole body testing is discussed later in this chapter (Section 7.3).

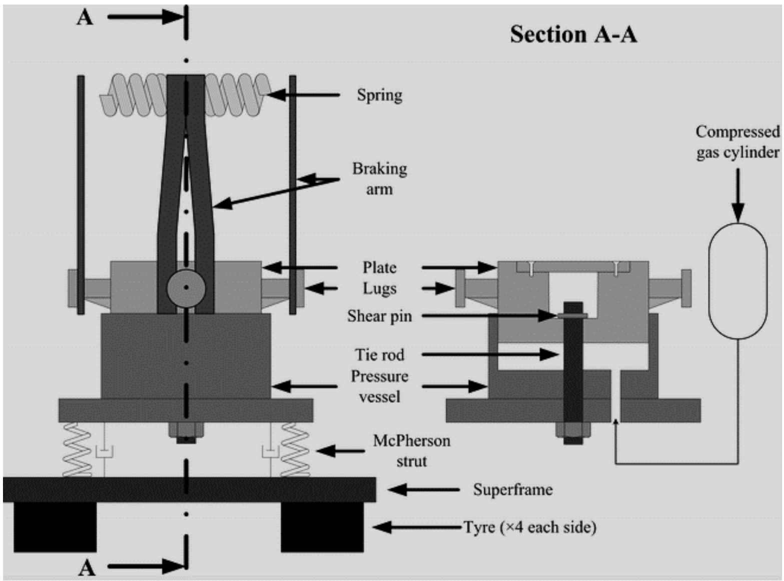


Figure 7.3: AnUBIS (anti vehicle underbody blast injury simulator) developed by the Centre for Blast Injury Studies, Imperial College London. Adapted from (Masouros et al. 2013).

Explosive Underfloor Mechanisms

Arguably the most realistic method to recreate explosive underfloor injury is the detonation of explosives beneath a fixed plate, to deliver tertiary blast to a desired specimen. The Test Rig for Occupant Safety System (TROSS^{TM}) utilises TNT beneath a simulated floor plate, to deliver a blast load, and this has once again been focussed on the testing of the lower extremity (McKay and Bir 2009). The main disadvantages of this testing strategy, is that they require a large area for testing, and they are not easily controlled and are not as repeatable a drop rig, (or traumatic injury simulator) (North Atlantic Treaty Organisation 2007).

7.2.4 Summary of Blast Testing Methods

The decision regarding which platform to utilise when assessing blast injury depends on whether assessing primary, secondary or tertiary injury, and the rate and type of loading selected. This can be summarised by the diagram below (Figure 7.4).

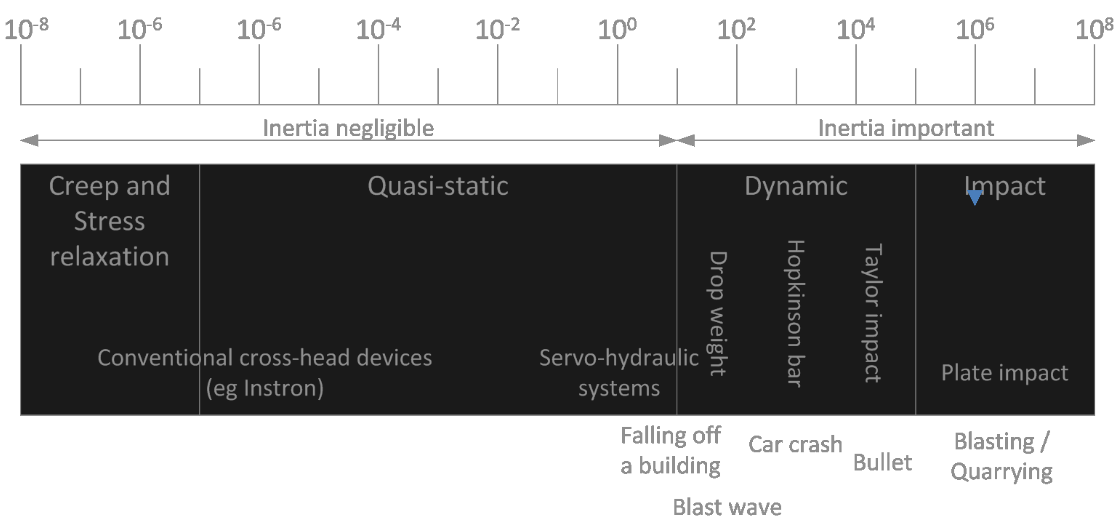


Figure 7.4: Summary of blast tests available depending on the type and rate of loading required in blast. Reproduced with permission from S Masouros.

7.3 Testing Surrogates

All the test mechanisms described above require a specimen to assess response. With regards to larger and more expensive consumables like human limbs or whole bodies, which also require a tissue licence and facilities for handling human tissues, mechanical surrogates can offer a viable replacement. The accuracy of the ability of a surrogate to replicate the human body is termed: 'biofidelity' and means: to represent the dimensions, mass, kinematics, and kinetics of the body under applied loading. Whole body surrogates can be more representative of a human form (Crandall et al. 2011a), however, there are challenges controlling the boundary conditions of larger specimens with multiple joints, and therefore whole body testing could be considered poorly controlled with low repeatability (Crandall et al. 2011a). Component testing (isolating specific body regions to be tested) can be much better controlled in terms of maintaining posture and repeatable applied loading.

7.3.1 Anthropomorphic Test Devices

Anthropomorphic Test Devices (ATDs) are used to model human injury. Historically they have been used to model injury in road traffic collisions. The most commonly used include the Hybrid III 50th percentile male dummy, Hybrid III midsize male dummy, the Test Device for Human Occupant Restraint (THOR), Side Impact Dummy (SID) the later more refined BioSID, and the Military Lower Extremity (Mil-Lx) ((Bailey et al. 2015; Kanianthra et al. 1993; Pandelani et al. 2010; Shaw, Crandall, and Butcher 2002; Youn et al. 2004). Whilst the Mil-Lx is specific to blast use, the focus is solely on the lower extremity (Pandelani et al. 2010). There are not currently any human dummies specific to whole body blast injury in active use, however the Warrior Injury Assessment Manequin (WIAMan) is a large United States run project aimed at producing an ATD specific to blast, and is currently being manufactured and validated. This project will enable physical testing using the WIAMan dummy and a subsequent Finite Element Analysis (FEA) model to ultimately produce injury probability curves for underbody blast injury in multiple body regions (Baker and Untaroiu n.d.; Pietsch et al. 2016) (Figure 7.5). Specifically with regards to the pelvis, tests have been validated against post mortem human surrogates (PMHS) specimens for this WIAMan project. This ensures accurate behaviour in differing postures, ensuring the biofidelity of the surrogate (Reed 2013).

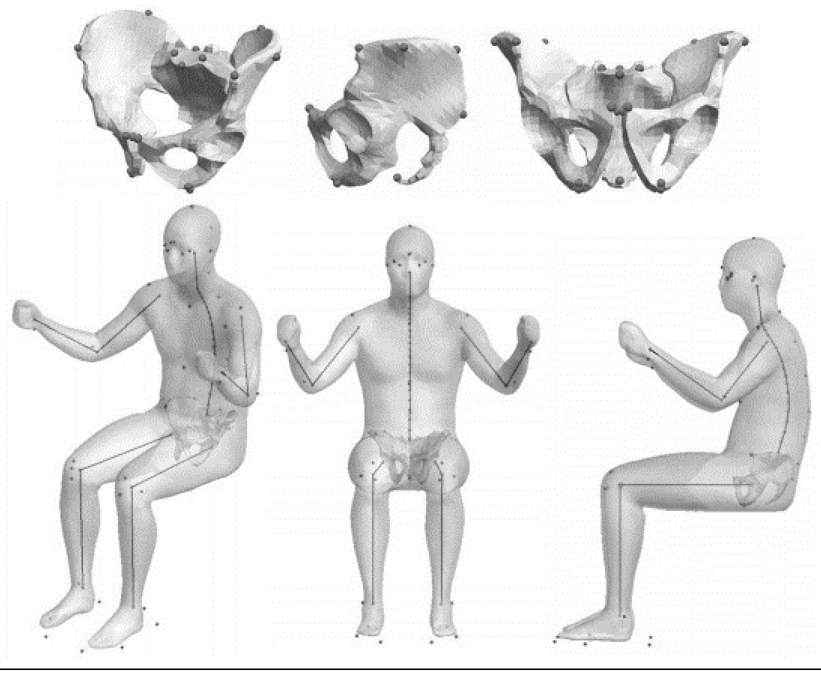


Figure 7.5: The WIAMan Project: A whole body testing surrogate specifically aimed at testing in blast injury. Anatomical reference points averaged across a spectrum of male body subjects lead to coordinates for individual body regions. The pelvis is shown as an example. Adapted from (Reed 2013).

Overall, the use of ATDs avoids some logistical and ethical issues with using PMHS, and the requirement of special licences and a lab set up appropriate for handling human tissues (Ramasamy et al. 2010a). The main disadvantage of the ATD is that they are only validated for a small number of test conditions, for example, the seated soldier in vehicle. There are no ATDs in existence at the present time designed to simulate the dismounted soldier subjected to IED blast loading.

7.3.2 Post Mortem Human Subjects

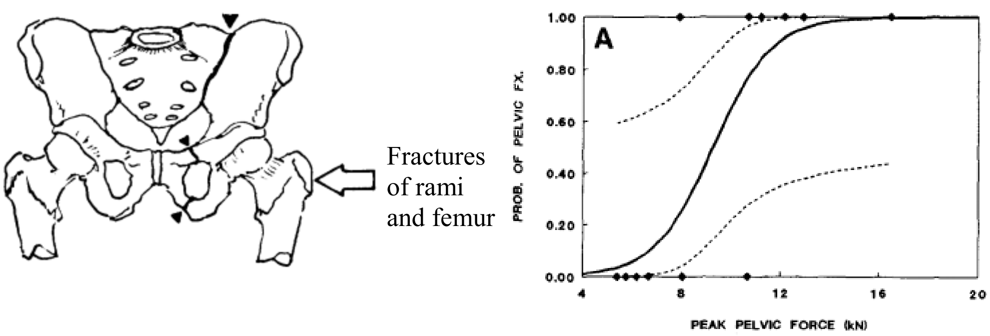
PMHSs have been used in physical injury modelling for over two hundred years (Crandall et al. 2011b). Although deceased tissue has some differences in behavioural characteristics than that of the live human due to post mortem changes and repeated freezing (Menz 1971), their exact representation of human structures means that their use can be advantageous. Embalming as preservation that was utilised in the early years was replaced by using fresh frozen specimens, as the embalming process caused unnatural increases in stiffness of soft tissues (Crandall J 1994). Bone specimens remain similar in structure regardless of the preservation method (Jamada H 1970). The most significant changes post mortem are within the cardiovascular and respiratory systems, due to cessation of blood flow, solidifying of blood vessels, and collapse of alveoli. This means that responses to applied loading may be inaccurate. Attempts have been made to ‘perfuse’ cadaveric specimens with intravascular volume, and inflate the airways, however, this is challenging in practice alongside an impact test (Shaw et al. 2002). Importantly, due to the atonal character of human musculature once rigor mortis has dissipated, there are difficulties in positioning of PMHS due to the resultant inability to retain a given posture. This is challenging and must be considered to ensure an accurate and repeatable positioning of specimens. Additionally, involuntary tensing of musculature has been noted as a reflex to anticipated impact in injures casualties, and will therefore cause a greater difference in mechanical properties of the PMHS compared with a live specimen (Özyörük et al. 1997). However in blast testing, rapid speeds of impact mean that this is less likely to be an important consideration in the reproduction of the blast environment.

7.4 Previous Physical Models of the Human Pelvis

There have been some attempts to recreate PI using physical models in the literature. These can be characterised into those not specific to blast testing, for other injury mechanisms, and those created specifically to simulate blast loading.

Physical Models not Specific to Blast

Early physical testing, as is much of the early physical injury modelling, was based around vehicle collisions. Viano et al (1989), when modelling injuries of the chest, abdomen, and pelvis in embalmed cadavers using a pendulum swing, focussed on injuries from lateral impact. Viano et al. (Viano, Lau, et al. 1989), recreated pubic rami fractures as seen in vehicle incidents. Sled impactors have also been used to simulate side impact of cadaveric specimens, some of which were specific to the pelvis (Cavanaugh et al. 1990), which also noted rami fractures, and SIJ disruption. Importantly, this study also produced injury curves demonstrating the biomechanical response to side impact, and probability of PI based on applied pelvic force, suggesting that a force of 14kN in lateral impact gives a 100% risk of pelvic injury (Figure 7.6).



(a) (b)

Figure 7.6: Pelvic injuries seen in lateral impact testing by Cavanaugh et al. (1990) (a) Diagram showing locations of injury post lateral impact (b) pelvic peak force as measured at the sacrum.

Salzar et al (2009) also performed side impact testing to cadaveric pelvises to simulate automobile crashes, which provided more detailed information on load transfer through the pelvis with lateral loading. It demonstrated that acetabular loading from side impact provided a more widespread loading via the PS and SIJs, and direct iliac wing side loading caused purely posterior loading at the posterior pelvis (SIJs and sacrum).

In terms of axial loading, ejection seat data presents some information on the behaviour of the pelvis on seated axial load (Evans and Lissner 1959), but most studies are focussed on the prevention of spinal fracture, rather than focussing on the pelvis, as spinal injury is common in ejection seat injuries, and pelvic fracture less so (Lewis 2002; Spurrier et al. 2015). Whilst tests for different injury mechanisms are useful in determining the tolerance of the human pelvis to impact, tests tailored specifically to blast injury are most useful.

Models Specific to Blast: Underbody Blast

It is difficult to simulate injuries due to explosions. Loading rates in UBB are not widely published, as this could pose a security threat and expose the vulnerability of the body under certain conditions (Scherer and Reed 2011). In addition, values are difficult to obtain, even if necessary security precautions are required. There is much variability in terms of the charge size, depth of burial, and type of explosive in devices, which are themselves notoriously variable. In addition there are vehicle design variables, including the standoff between the ground and the undercarriage. Therefore, loading rates applied to cadaveric testing are approximated. Bird et al (2004) performed vehicle testing in an attempt to determine floor deformation using 10kg of TNT, however, these tests did not present deformation or velocity data. These tests often experience transducer failure, produce inconsistent results, and are costly (Ramasamy et al. 2010b). In addition, there are many variables concerning the casualty, for example, position in the vehicle, applied personnel protective equipment, in-vehicle restraints, and the mass of the individual. In experimental testing, all of these variables must be considered.

There are few laboratories worldwide who have performed physical testing of the pelvis under simulated blast loading, and all of these are in the mounted casualty. Yoganandan et al (2014) assessed inferior to superior loading at the pelvis-sacrum-lumbar complex, in order to further understand the relationship between load transfer at the pelvis in the seated position, and the subsequent load transfer proximally involving the spine. They used a sled impactor (Figure 7.7) to administer a variety of input pulses (triangle, saw-tooth and sigmoidal), durations (9-60g, and time to peak between 6-46ms) and maximum acceleration (2.96-12.46m/s) to 5 PMHSs. The differing input pulses was for the purpose of simulating the level of energy absorbing material at the seat area: triangle shaped impulses simulating no padding, and saw-tooth shaped impulses simulating a lengthened load distribution due to seat padding, and a sigmoidal shaped impulses to reproduce the ‘bottoming out’ effect of energy absorbing seats. These tests conclude that shorter duration impulses are more likely to cause PIs and spare the spine, and softer, longer duration impulses are more likely to transmit load axially, and cause spinal injury in addition to pelvic injury. This is likely to be due to shorter impulses transmitting load to structures in the immediate vicinity, and longer durations recruiting further anatomical regions to absorb load. Types of pelvic injuries seen were pubic rami fractures in two cases, one coccygeal fracture and three cases of SIJ separation. The rami and coccygeal fractures are representative of the clinical data in Chapter 5, however, the SIJ injuries (in the mounted casualty) are not. This could be due to either the boundary conditions of the experiments or an unlikely loading pulse. Alternatively, the clinical data did include those casualties who died of additional injuries, so cases of SIJ separation in high rate loading may have not been captured within the dataset in Chapter 5.

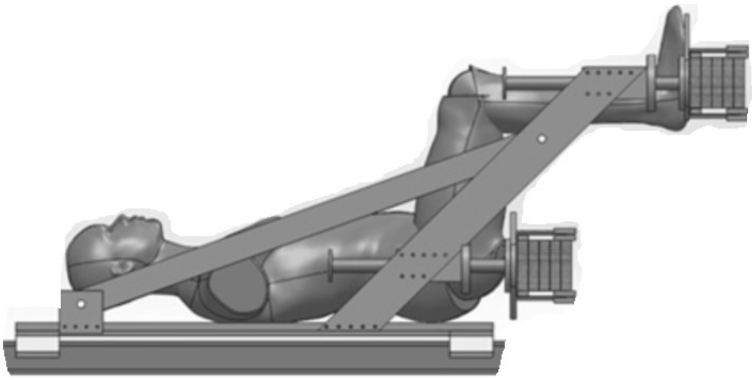


Figure 7.7: A diagram of the type of experimental set-up used by Yoganandan et al.(2014).

Danelson et al (2015a) developed an accelerative loading fixture (ALF), otherwise known as a ‘blast buck’. It comprises two rigid seats within a supporting cage like structure (Figure 7.8). A deformable floor insert, which is replaced after each test, is impacted using a pneumatically driven anvil to simulate underbody blast. Their study comprised a comparison of the behaviour of PMHS and the Hybrid III ATD, in which some deficiencies were realised in the ATD (greater stiffness). This confirmed a specialised ATD for use in underbody blast would need to be created. Pelvic fractures were seen in 64% of the PMHSs, including superior and inferior pubic rami fractures and acetabular fractures, a realistic clinical picture comparable with the analysis in Chapter 5. In this test, pulses of a shorter duration and higher magnitude impacts were more likely to lead to fracture.

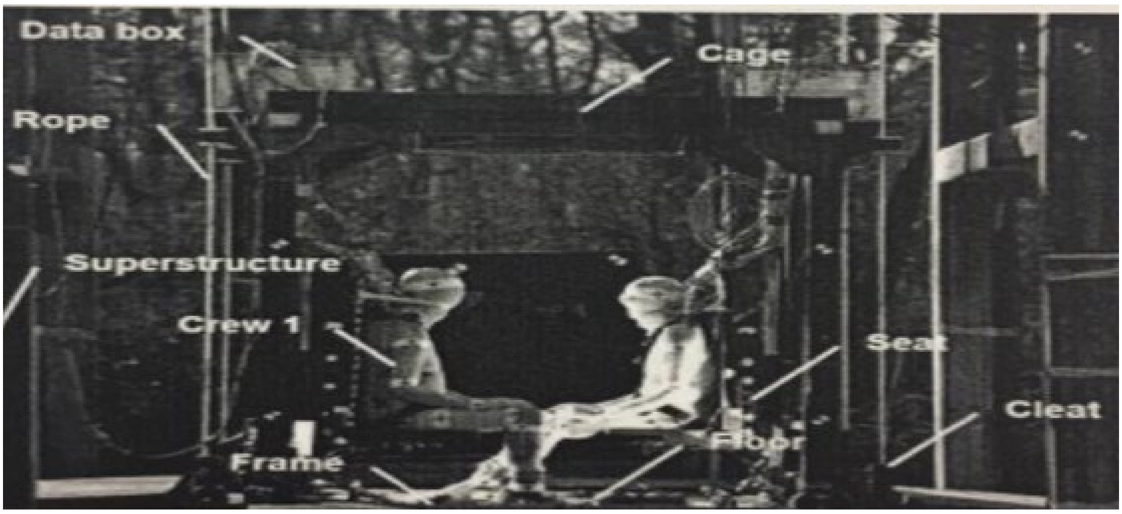


Figure 7.8: Photograph of the accelerated loading fixture (ALF) or 'blast buck' developed for high rate vertical loading. Seen here using an ATD (left) and PMHS (right). Adapted from Danelson et al. 2015.

Bailey et al. (2015) looked at pelvic underbody blast using 10 PMHSs and the ODYSSEY test rig, which utilises two separate platforms, a seatpan and a footpan to support the pelvis and lower limbs respectively and using a pneumatic system and hammer technique to apply UBB loading to these platforms (Figure 7.9). Tests were performed with the addition of the subject wearing combat boots, and a 5 point harness restraint.

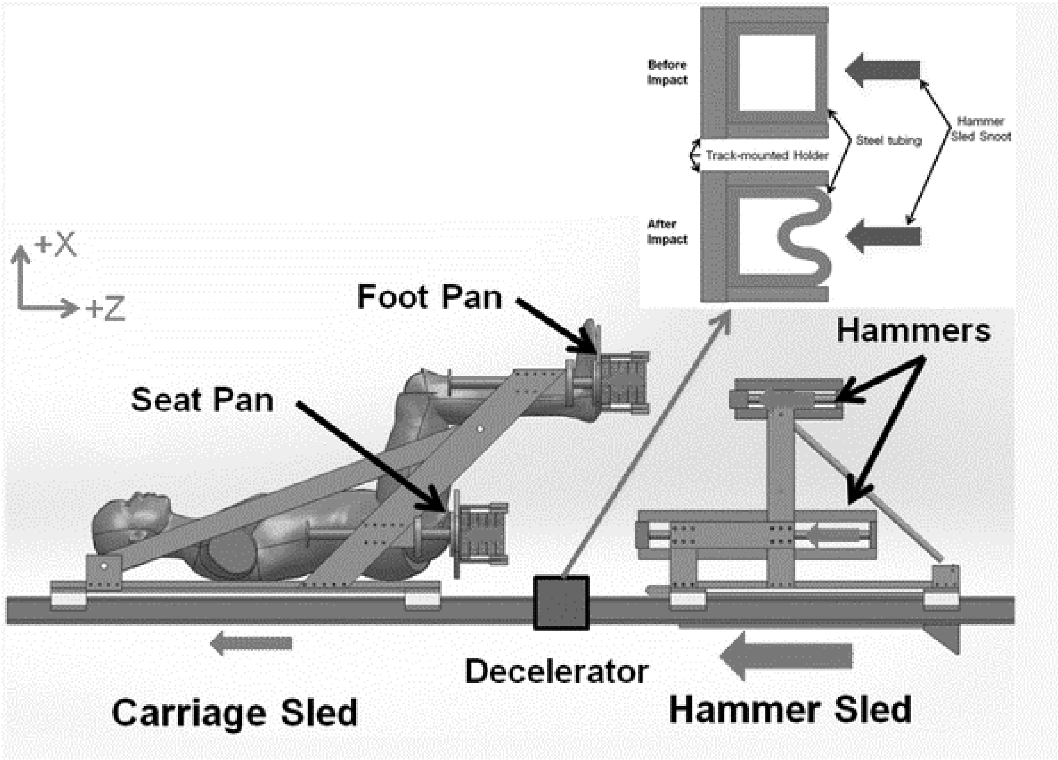


Figure 7.9: A diagram of the ODYSSEY underbody blast injury simulator at the University of Virginia. Adapted from (A. M. Bailey et al. 2015)

This study produced pelvic injury risk curves, and subsequently predicted a 50 percent chance of PIs at an impact velocity of 4.04 m/s and at an acceleration of 278g, both measured at the sacrum. These tests achieved two sacral, 7 (two bilateral) rami and 4 acetabular fractures (3 of which were bilateral), which is representative of realistic underbody blast injuries as presented in the clinical data in Chapter 5.

Models Specific to Blast: Dismounted Blast

To the author's knowledge, there are no tests in the literature to date that simulate the blast pelvis in the standing position, either in mounted or dismounted casualties. Although the previous testing methods described in this chapter are based on casualties in the seated position, the tests provide a guide on loading rates required to cause PI (A. M. Bailey et al. 2015; Cavanaugh et al. 1990; Danelson et al. 2015b; Salzar et al. 2009; Viano, Lau, et al. 1989; Yoganandan et al. 2014). Additional useful techniques used in these tests to help control boundary conditions (such as maintaining correct pelvic postures during testing and gauging methods and locations) will provide important information to development of new testing strategies.

7.5 A Physical Model of the Dismounted Pelvic Blast Injury

7.5.1 Hypothesis

It has been confirmed by analysis of recent casualty data from explosive incidents causing PI that, when compared to mounted, the dismounted casualty sustains the most fatal pelvic fractures, commonly opening at the SIJs and PS. One theory of this mechanism, described in Chapter 5, is that axial load transmitted via the femoral heads in the standing position. This was deemed the injury mechanism in which preventative techniques may be futile, therefore, accepting or refuting this injury mechanism would be vital to the picture of potential injury mitigation. Therefore a laboratory experiment was designed aiming to determine whether the axial load delivered via the femur leads to an injury pattern that is seen in the dismounted soldier following blast incidents.

7.5.2 Materials and Methods

Ethical approval for these tests was granted from the local regional ethics committee at the Imperial College Healthcare Tissue Bank. Cadaveric specimens were provided by the licensed tissue laboratory Life Legacy, Arizona, USA. Tissue donors had consented to their use for scientific research, as per the protocol of Life Legacy. All specimens were screened for blood borne and other communicable diseases prior to shipment. All experiments were conducted at Imperial College London, in a laboratory designed and approved for human tissue experiments in accordance with the Human Tissue Act 2004.

7.5.3 Test Rig Design

Assistance with the planning and execution of this design was gratefully received from Dr D Carpanen, Dr G Grigoriadis, Dr N Newell, Dr A Christou, and Dr S Masouros. An in-house-built drop rig was utilised for this experiment, with modifications required for specifically testing the pelvis added into the experimental design. This included an x-y plate at the base of the rig to move the pelvis into position under the impactor, a harness to hold the femur in an upright position, and specially designed and manufactured pots for the spine, contralateral pelvis and distal femur.

During this experiment it was essential that the specimen was supported in realistic posture, meaning that boundary conditions at the spine, and both hip joints were adequately held in the correct posture, to ensure specific load delivery axially at the femoral head in the standing position. The drop tower rig was used in order to transmit the axial force in the following configuration (Figure 7.10).

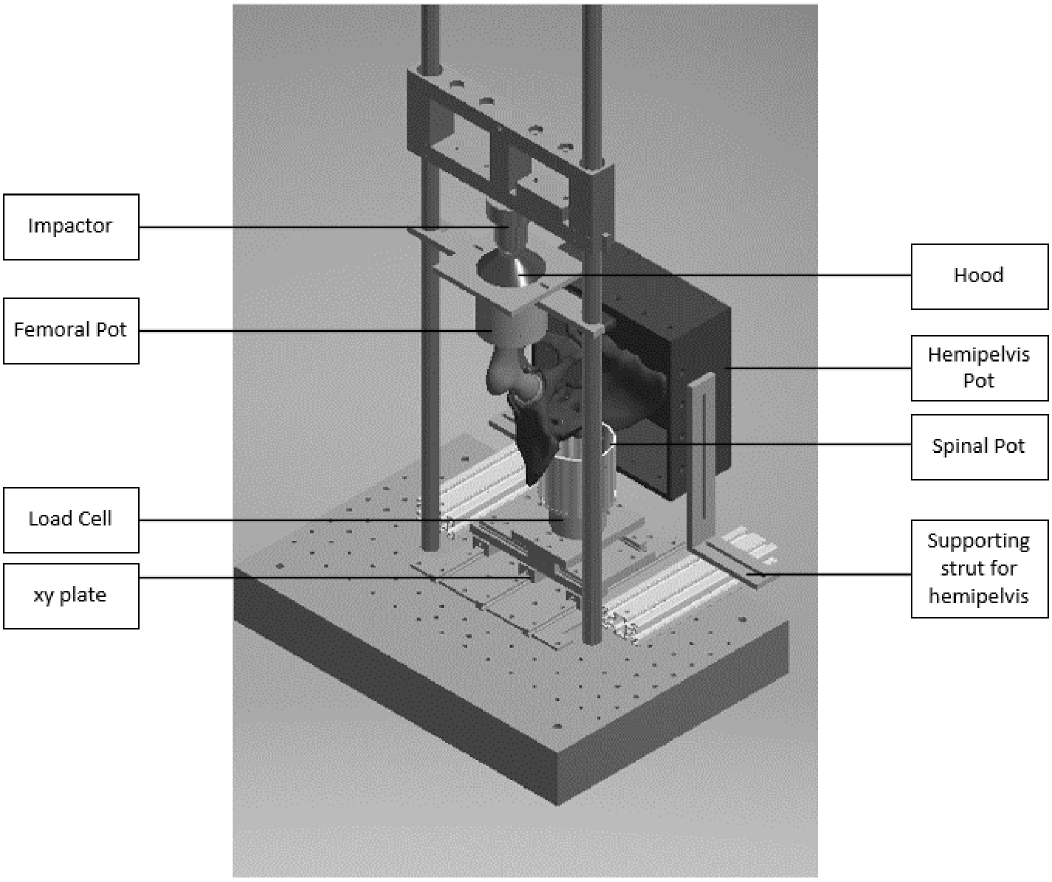


Figure 7.10: Diagram of the test set-up within the drop rig to investigate the hypothesis that pelvic injuries are caused by axial load delivery via the femur.

This test set up rigorously constrains the pelvic specimen at the spine and the contralateral hemipelvis to allow the isolation of the testing side. This enables the delivery of axial force into the ileum via the femoral head, to assess the effect of pure axial load on the pelvis.

7.5.4 Specimen Preparation

A total of four male fresh-frozen pelvic specimens were obtained for this study. Specimens were sectioned from the L1 lumbar vertebrae, to the mid femur. The specimens were stored at a temperature of -20°C. The specimens underwent pre-test CT scanning (Siemens Somatom Definition AS 64, Erlangen, Germany) at the RCDR, RCDM, Birmingham, UK to exclude damage in transit, or pathology. The test specimens were thawed for 36 hours prior to testing. A summary of the specimen details is presented below (Table 7.1).

Specimen Number	Age (yrs)	Height (cm)	Weight (kg)	Cause of death
1	54	182	67.9	Lung Cancer
2	57	155	73.1	Stroke
3	52	169	76.0	Oesephageal bleed
4	49	180	64.9	Glioblastoma

Table 7.1: Cadaveric specemin details.

Specimen Preperation

The specimens arrived devoid of abdominal viscera, but with retroperitoneal vasculature intact (Figure 7.11). Proximally the specimen was sectioned through the L3 vertebral body. The soft tissues (skin, subcutaneous tissue and selected muscle) were moved to allow access to the SIJs and PS for instrumentation, and to the spine and femur to allow bone to be secured with mounting pots. Distally the right femur (stabilising) was sectioned at the femoral neck. The contralateral (testing) femur was divided at the mid-thigh, and removed of tissues distally to allow adherence to the pot. A fixed position either side of the SIJs and PS was exposed to the bone for application of strain gauges (C2A-06-062LW0350, Vishay, Basingstoke, UK), and markers (white headed pins) were also fixed (pin into bone) to assess dynamic deformation using the high speed video (Section 8.5.5). The potting of the specimens, the spine, femur and contralateral hemipelvis allowed accurate control of boundary conditions such that the load could be transferred axially via the femoral head. This potting sequence is described in the following sections.

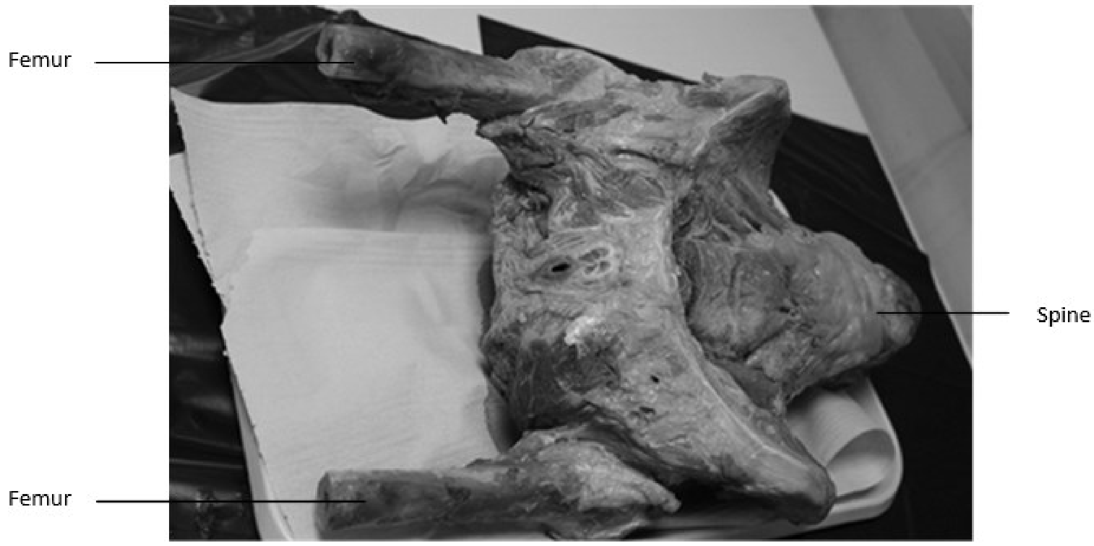


Figure 7.11: Photograph of pelvic specimen prepared for testing.

7.5.5 Testing Protocol

Specimen Potting

The spine, testing femur and supporting hemipelvis are required to be strictly controlled in terms of a realistic posture, and supporting, repeatable test set up to enable controlled loading at the femur. Pots were specially manufactured to hold these three structures, and secured to the rig.

Spinal Potting

The spinal vertebrae were initially fused to the sacrum using external fixator screws down the centre of the body of the vertebrae, into the main body of the sacrum, to ensure fixation of the spine. The spine was potted from the L3 vertebra to the sacrum using bone cement (polymethyl methacrylate, PMMA) within the specially designed aluminium pot. The pot was lubricated with petroleum jelly to allow for easy removal post-test, as the aluminium pots would interfere with cross sectional imaging. The spine was inverted 180° to enable potting to take place. The potting angle was calculated using a specially produced measuring tool. This was manufactured to ensure the pelvic angle was consistent with that of a standing posture (Figure 7.12). The technique used widely to measure the angle between the ASIS and the PS, is ensuring the standing position, are both at 90° to the horizontal plane. The tool was placed on both ASIS, and the PS, and the angle of this measured to be 90° (Chanplakorn et al. 2011; Lazennec, Brusson, and Rousseau 2013). Once in position, external fixator screws were used to fix the spine in position within the pot prior to pouring PMMA into the pot to secure the spinal column through to the sacrum.

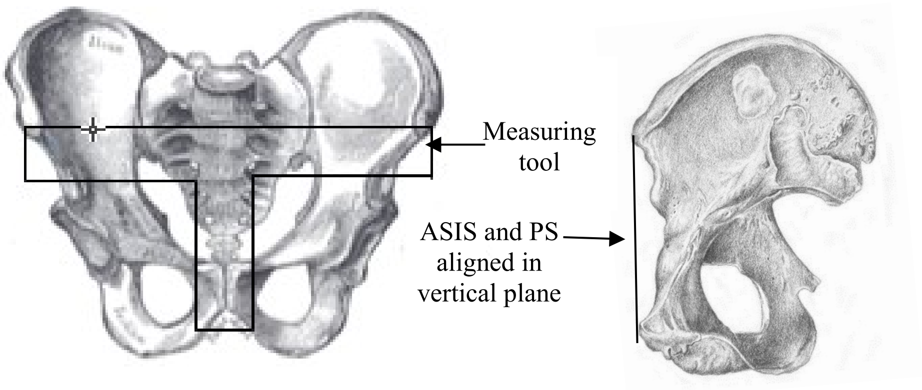


Figure 7.12: Diagram showing the measurement of the pelvis in the standing posture: (a) measurement tool demonstrating the plane between the pubic symphysis and sacroiliac joints at 90° to the horizontal plane, or, (b) vertically aligned. Adapted from Gray's anatomy, 2000.

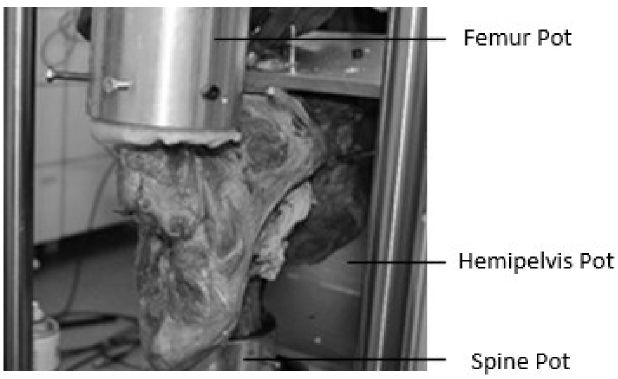
Femur Potting

The femur was potted to replicate its position when standing, which has been described to make minimal (<1°) difference to the position at the femoral neck (Croce, Cappozzo, and Kerrigan 1999). The femur was held in position within the pot using fixation screws perpendicular to the pot and bone before being fixed with PMMA (Figure 7.13).

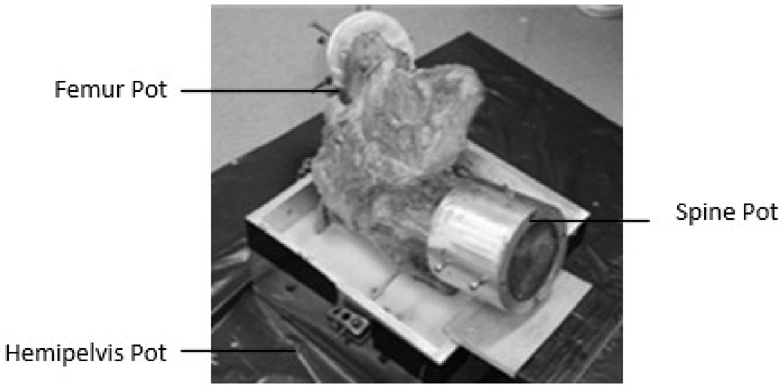
Figure 7.13: Photograph of the potting. The specimen is held in an upright position with the femur placed in its pot while the bone cement hardens.

Hemipelvis Potting

The hemipelvis was the final region of the pelvis to be potted. The specimen was positioned within the drop rig to ensure the accurate anatomical position was maintained, to allow the spinal pot to be aligned with the load cell, and the femoral pot to be aligned with the impactor. The pelvis was held in position using external fixator screws before being fixed with PMMA (Figure 7.14).



(a)



(b)

Figure 7.14: (a) Photograph of hemipelvis potting and (b) specimen in the drop rig being aligned prior to potting.

7.6 Final Set Up

The potted specimen was screwed on the load cell within the drop tower, manoeuvred into position under the impactor, and onto the load cell using an x-y plate. The final test set up is shown in Figure 7.15.

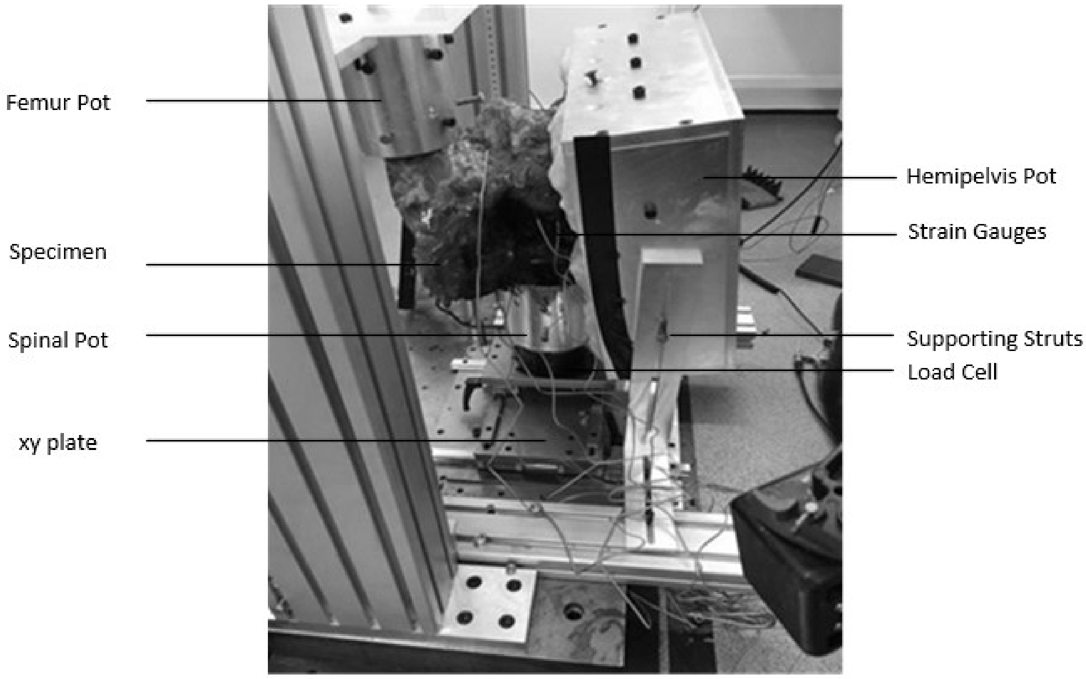


Figure 7.15: Photograph of the final test set-up.

7.6.1 Instrumentation

Monitoring of the specimen during the experiment was performed using the following methods, demonstrated in Figure 7.16:

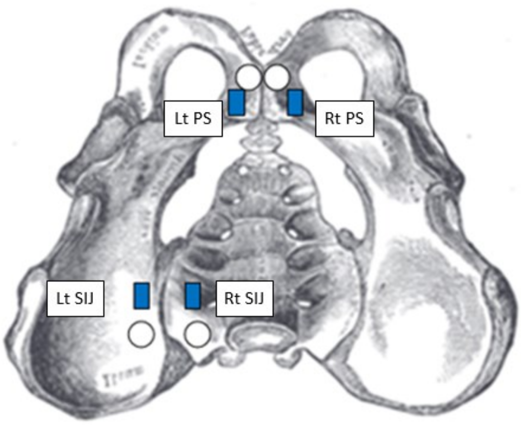
a. Strain gauges (C2A-06-062LW0350, Vishay, Basingstoke, UK) either side of the SIJs and PS (Figure 7.16a);

b. Markers (generic stationary pins) either side of the SIJs and PS (Figure 7.16a);

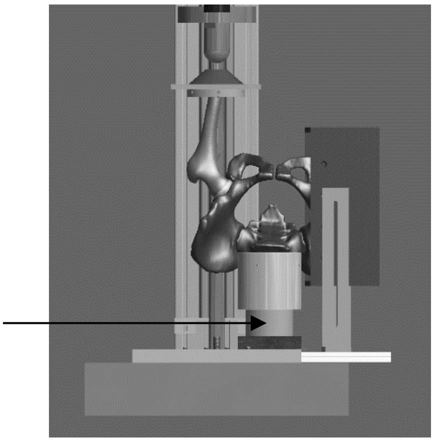
c. Load cell beneath the spinal pot (Figure 7.16c);

d. High speed video (Phantom V210) in anterior-posterior and lateral dimensions (Figure 7.16d).

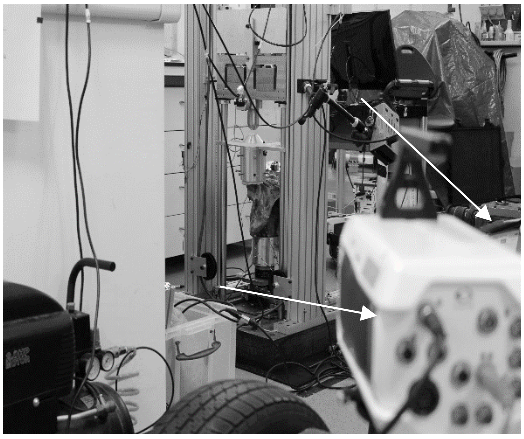
Strain gauges, the accelerometer, and the load cell were connected to the PXIe data acquisition system using customised LabVIEW software (NI Instruments, Austin, TX, USA) to store data obtained during testing.



(a)



(b)



(c)

Figure 7.16: Experimental Set-up. (a) Placement of strain gauges and markers either side of the pubic symphysis and sacroiliac joint; strain gauges (blue rectangles) and white markers (white circles). (b) Load cell (arrow) (c) HSV in two planes (anterior posterior and lateral), cameras arrowed.

7.6.2 Impact Conditions

The tests were performed in sequence, with differing loading conditions and specimen specifics based on the outcomes of the previous test. The loading conditions are summarised in the table below (Table 7.2).

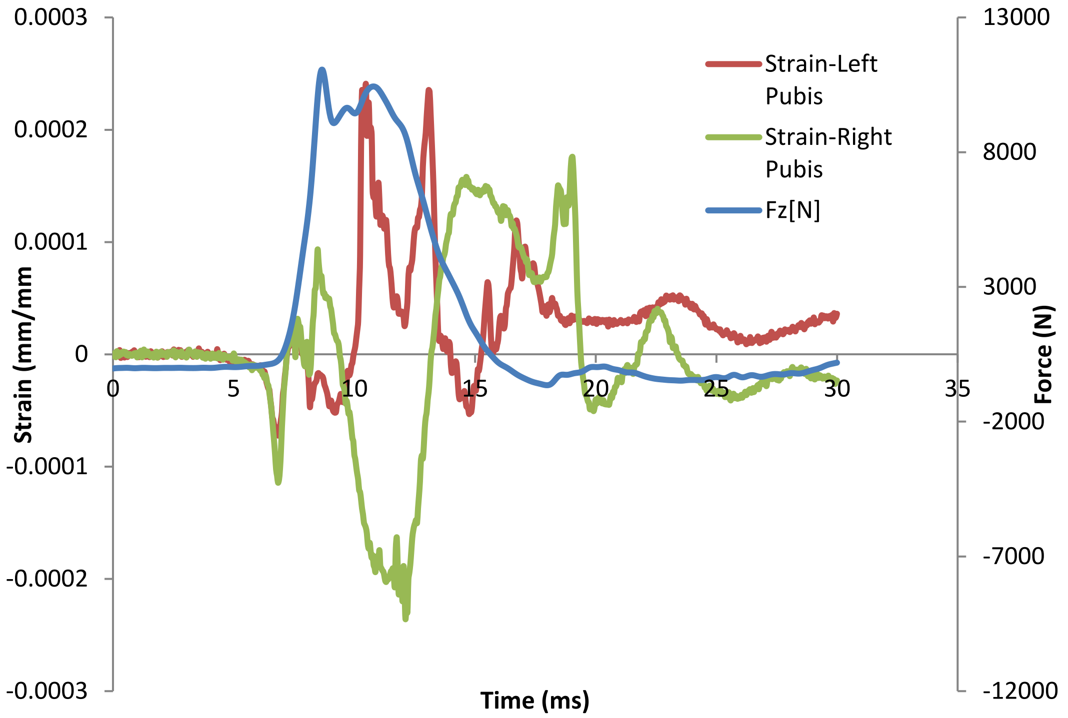
Test	Specimen	Mass (kg)	Speed at Impact (m/s)
1	Intact	7	5.73
2	Intact	20	5.71
3	PS Divided	20 Plus bungee	7.12
4	PS and Anterior SI ligament divided	20 Plus bungee	6.09
5	PS and anterior SI ligament divided	20 Plus bungee	7.22

Table 7.2: Testing protocol: Loading conditions and specimen details of each test. A decision on a subsequent test was based on the outcome from the previous.

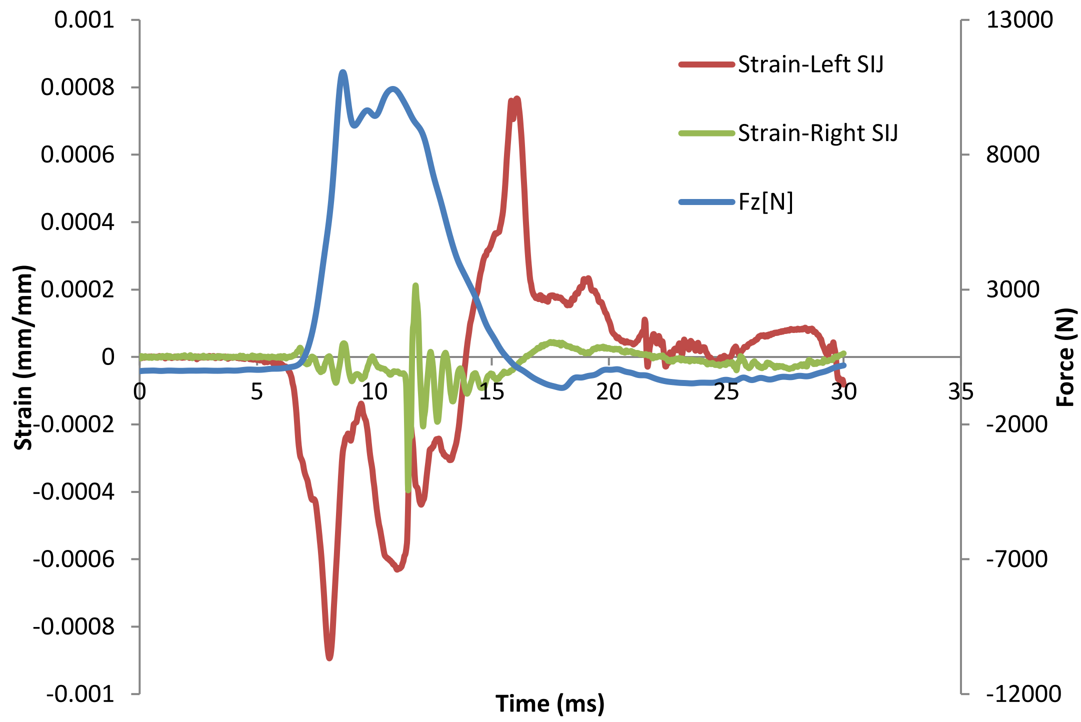
7.7 Experimental Tests

Test 1: Intact Pelvis

This first test was performed on an intact specimen, with axial load applied via the femoral head as per the test protocol (Table 7.2). This test recorded a peak axial force of 11.0kN (Figure 7.17a,b). Strain gauges at both sides of the PS demonstrated very similar strain, an initial compression followed by tension (Figure 7.17a). These matching waveforms could suggest no shear is taking place at this joint, as this would be more likely to produce opposing waveforms. The SIJs differ, with the right SIJ showing little activity, and the left SIJ showing a brisk compression (Figure 7.17b). These differences could be evidence of some shear activity.



(a)



(b)

Figure 7.17: Test 1: Axial force measured at the spine, and strain measured at (a) the pubic symphysis and (b) the sacroiliac joints. Positive strain is tension; negative strain is compression.

High speed video (HSV) showed some movement of the PS to indicate dynamic shear, but with return to the original position post-test (Figure 7.18). The post-test image did not demonstrate any fracture of the pelvis or the femoral neck (Figure 7.19).

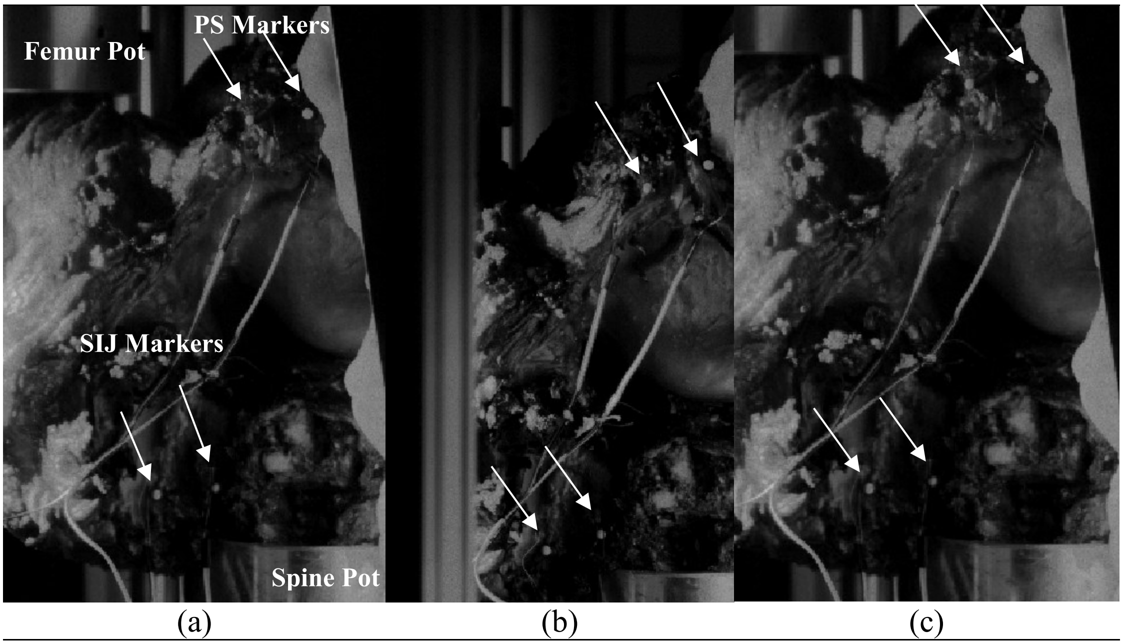


Figure 7.18: Test 1: Still images from the high speed video at the initiation, mid-point and final positions (3, 18 and 25ms) during the test, demonstrating deformation of the left hemi pelvis in relation to the right, based on the white markers either side of the pubic symphysis and sacroiliac joints (arrowed). Return to the original position occurs when loading is ceased (i.e. markers return to horizontal alignment).

Figure 7.19: Test 1: Post-test axial CT scan, demonstrating no injury.

Test 2: Intact Pelvis

This test was a repeat of test 1 whereby pure axial load was applied on an intact pelvic ring, to ensure repeatability of the experiment under these test conditions. The peak axial force recorded was 11.0kN. The PS (both sides) go from compression to significant tension. Unfortunately, the strain gauge of the right SIJ did not produce a reading (it was dislodged in the impact), whereas the left SIJ showed a rapid compression followed by tension (Figure 7.20).

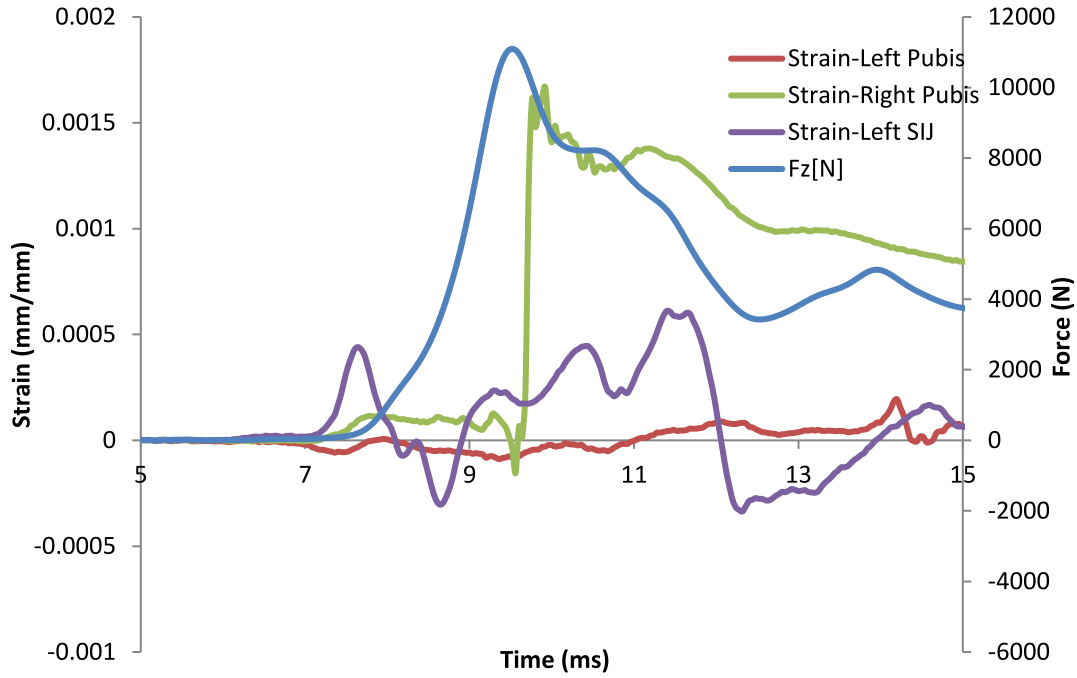
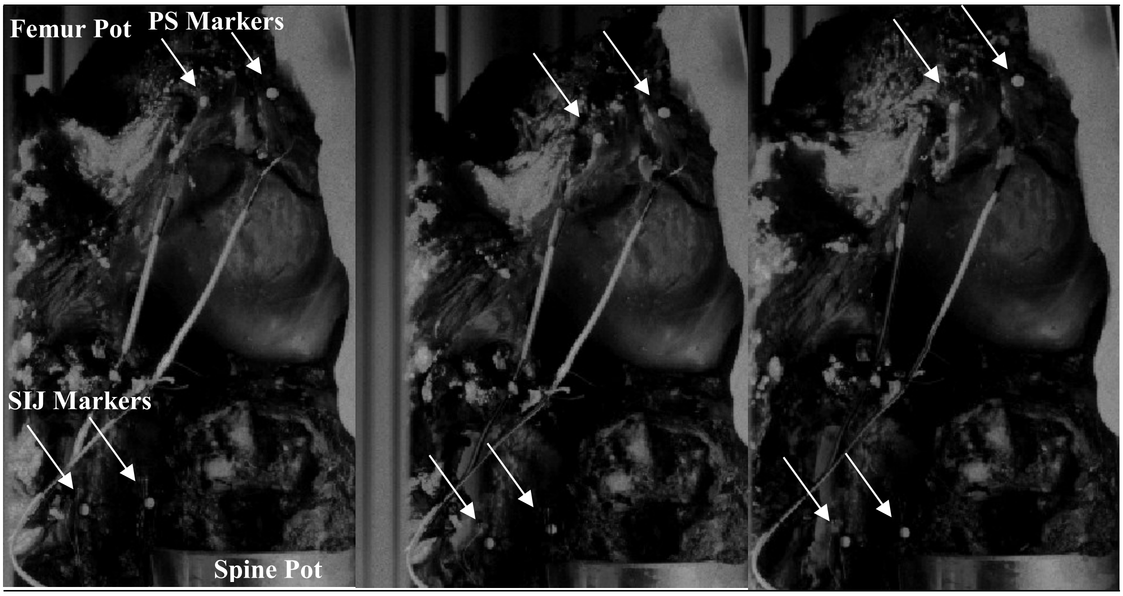


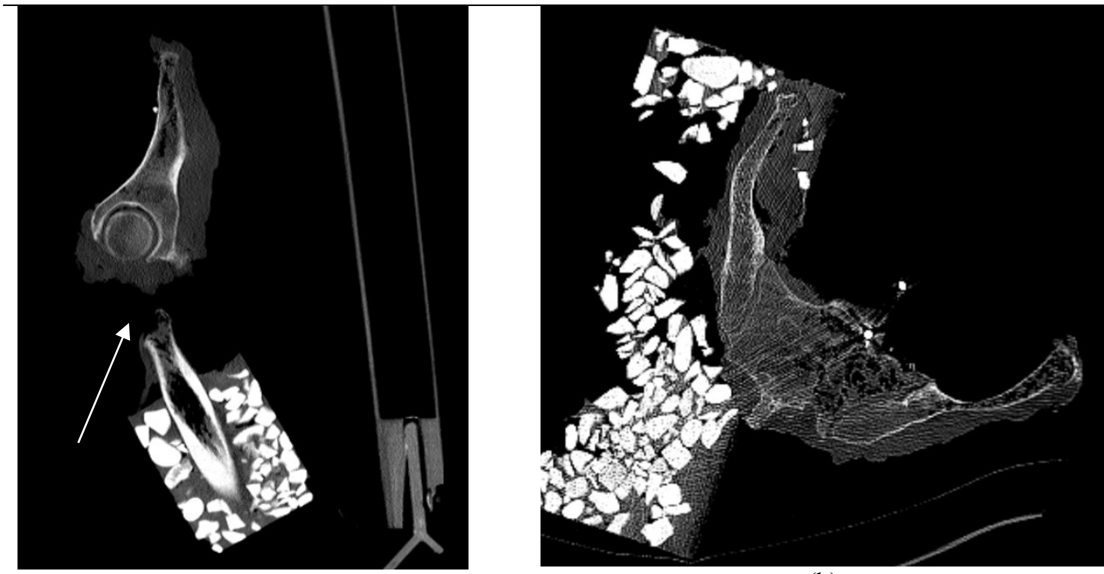
Figure 7.20: Test 2: Axial force measured at the spine, and strain measured at the pubic symphysis and the sacroiliac joints. Positive strain is tension; negative strain is compression.

The HSV demonstrated some movement of the PS in a shearing direction, but return to a normal anatomical position on removal of the applied load (Figure 7.21). Analysis of post-test CT scans show a divided femoral neck, but no further fractures of the pelvis, with the PS and SIJs remaining intact (Figure 7.22). This failure at the femoral neck could explain the reduced peak force measured at the load cell compared to Test 1 (3kN versus 11kN).



(a) (b) (c)

Figure 7.21: Test 2: High speed video still images at the initiation, mid-point and final positions (3, 18 and 25ms) demonstrating deformation of the left hemi pelvis in relation to the right, based on the white markers either side of the pubic symphysis and sacroiliac joints (arrowed).



(a) (b)

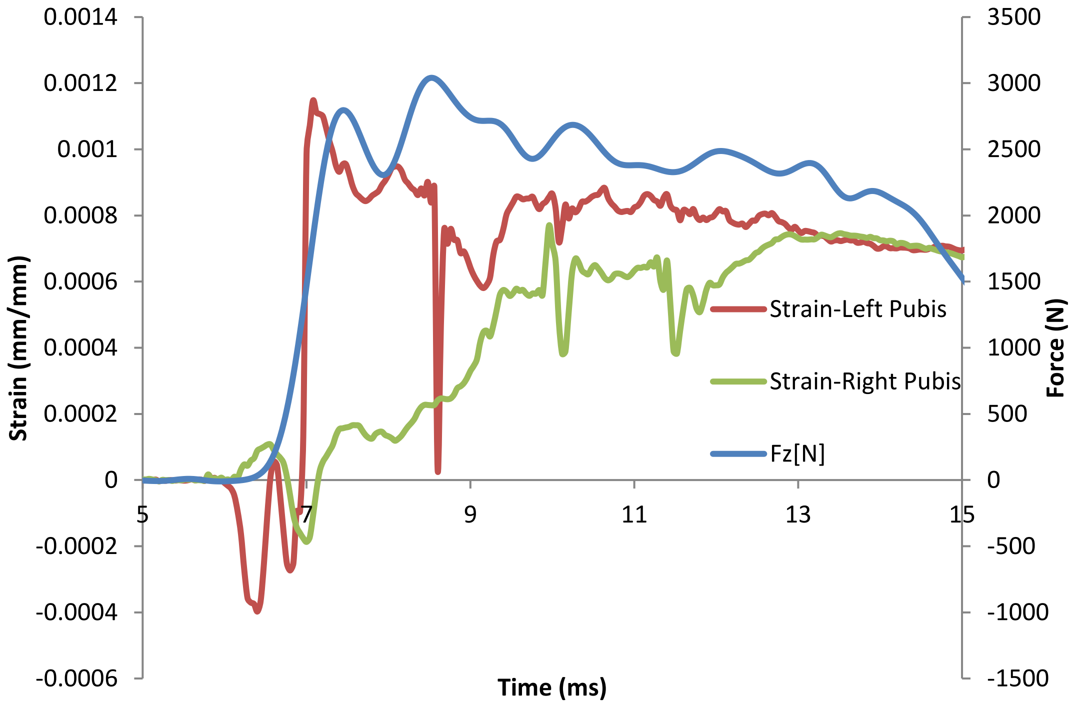
Figure 7.22: Test 2: Post-test CT scans. (a) Complete fracture of femoral neck and complete separation of the remaining femur and femoral pot (arrowed). No other pelvic injuries were identified on imaging (b). Pubic symphysis and sacroiliac joints are intact, seen on axial view.

Test 1 and 2: Summary and Conclusion

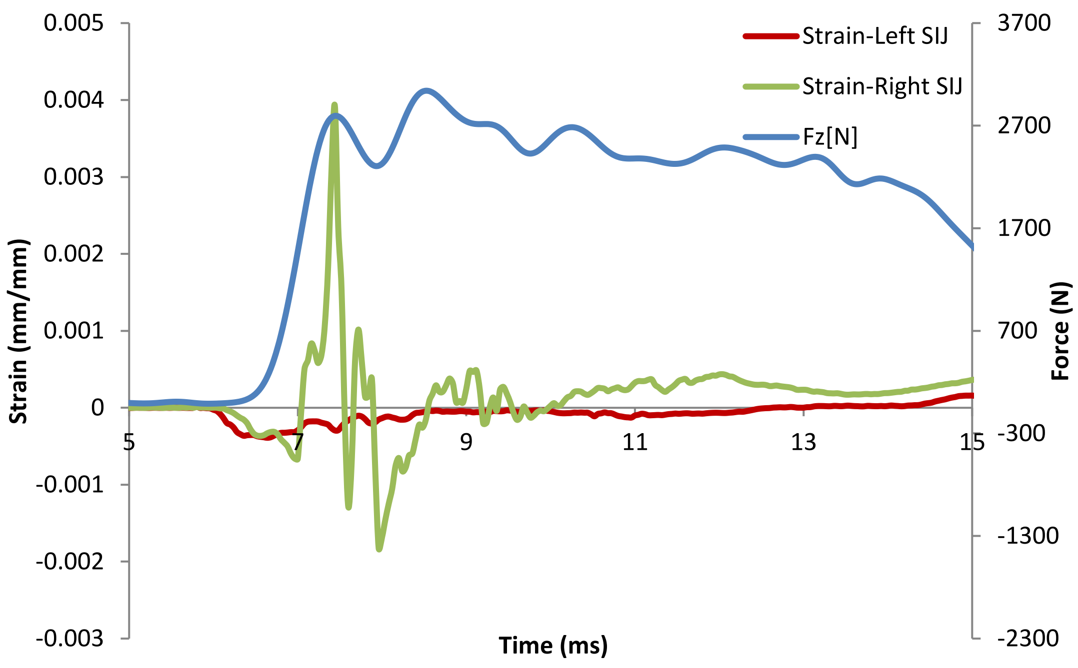
These two tests demonstrate that axial load delivered via the femoral head does not lead to pelvic fracture, but to preferential fracture at the femoral neck. Therefore an additional mechanism of pelvic fracture may be important. Flail has been hypothesised as an injury mechanism in TA of the lower limb (Chapter 3 Section 3.5), and may be important in the mechanism of pelvic fracture. If flail were implicated, it could be the cause of an initial opening at the PS. Therefore, in the following tests, the PS was opened, to simulate flail, and axial load delivered purely to the posterior pelvic ring, via the SIJs, was simulated.

Test 3: Sacrificed Pubic Symphysis

Due to specimen availability, the specimen used in Test 1 (which did not demonstrate any injury) was used for this test. The PS was divided completely using sharp dissection down the centre of the PS cartilage. In a sacrificed PS, the peak axial force recorded in this test was less than the previous (3.0kN) (Figure 7.23a,b). Strain in the left and right pubis show opposing responses (i.e. one in tension and one in compression), which suggests a shearing force (Figure 7.23a). The left SIJ shows minimal strain, with the right side of the SIJ showing an initial compression (Figure 7.23b).



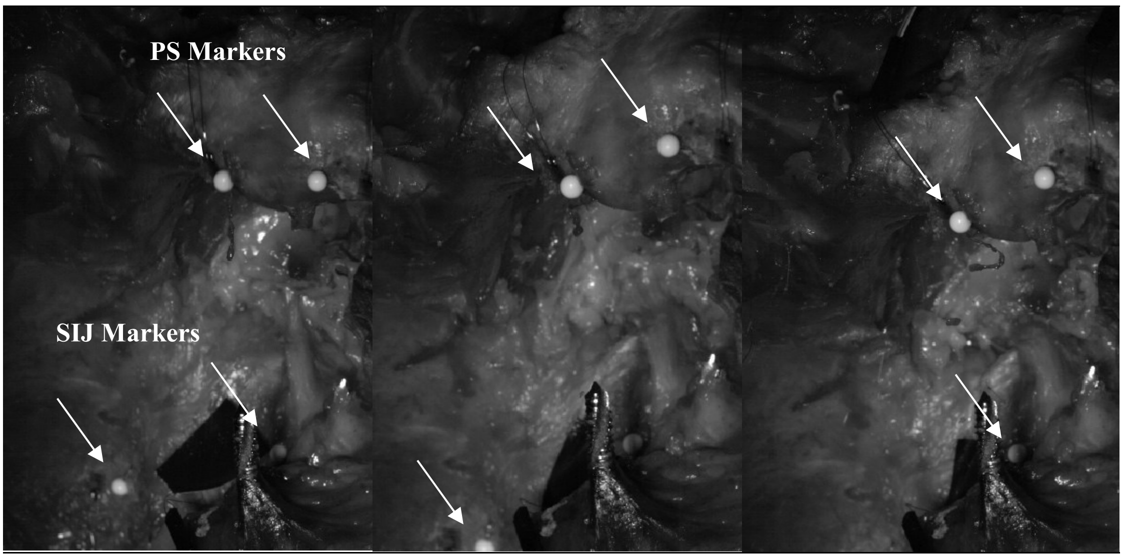
(a)



(b)

Figure 7.23: Test 3. Axial force measured at the spine, and strain measured at (a) the pubic symphysis and (b) the sacroiliac joints. Positive strain is tension; negative strain is compression.

HSV of this test also produced a shear type movement that resolved post impact (Figure 7.24). Post-test CT scan demonstrated an oblique fracture through the femoral neck. No pelvic fracture was identified (Figure 7.25).



(a) (b) (c)

Figure 7.24: Test 3: HSV still images at the initiation, mid-point and final (3, 14 and 16ms) positions demonstrating deformation of the left hemipelvis in relation to the right, based on the white markers either side of the PS and sacroiliac joints (arrowed).

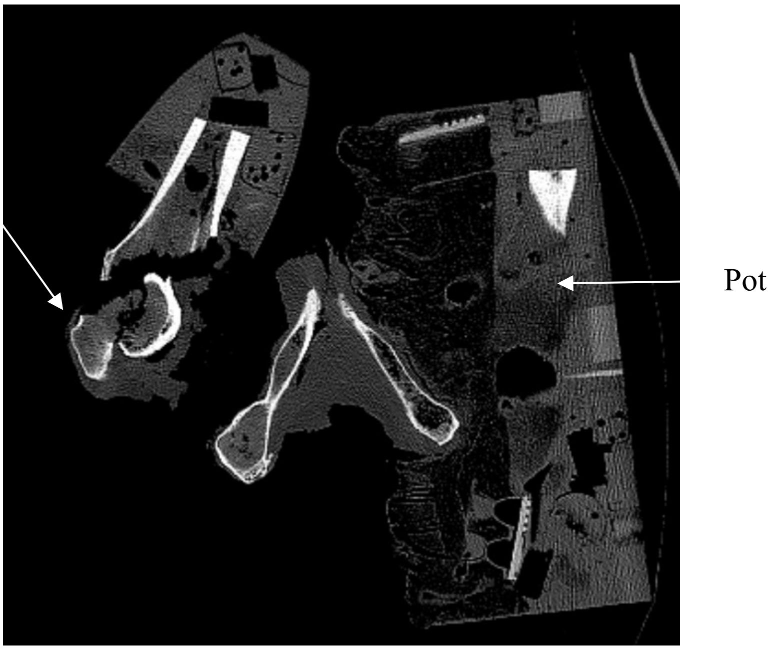
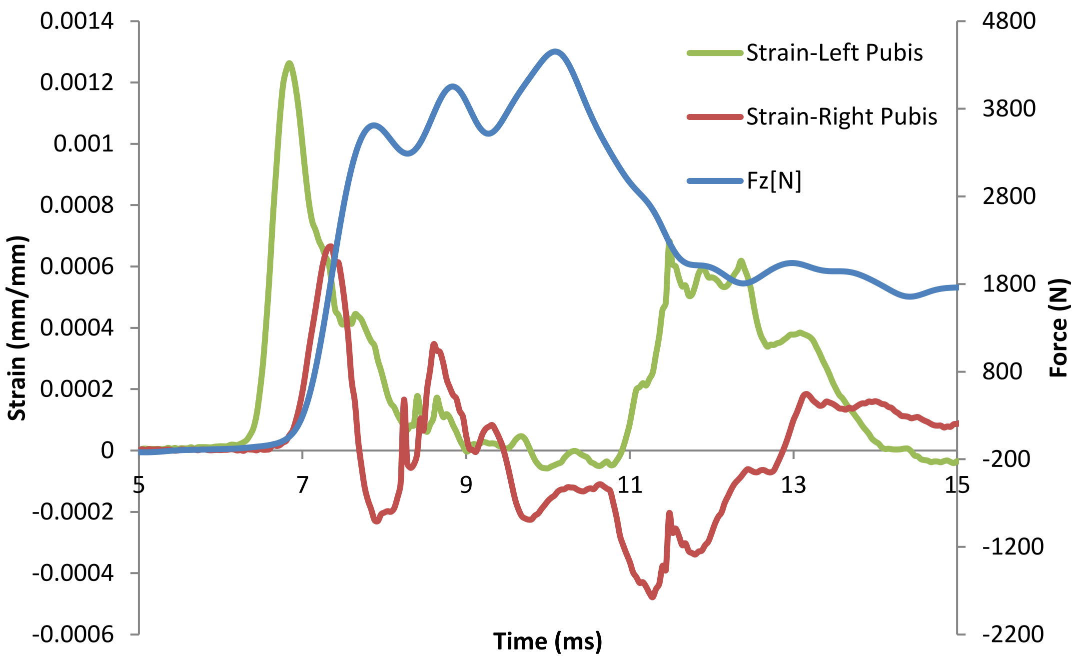


Figure 7.25: Test 3: Post-test axial CT image with divided pubic symphysis. CT demonstrates intertrochanteric fracture of the left femoral neck. This specimen did not sustain any other fracture, and bilateral sacroiliac joints remained intact. Arrow indicates femoral neck fracture.

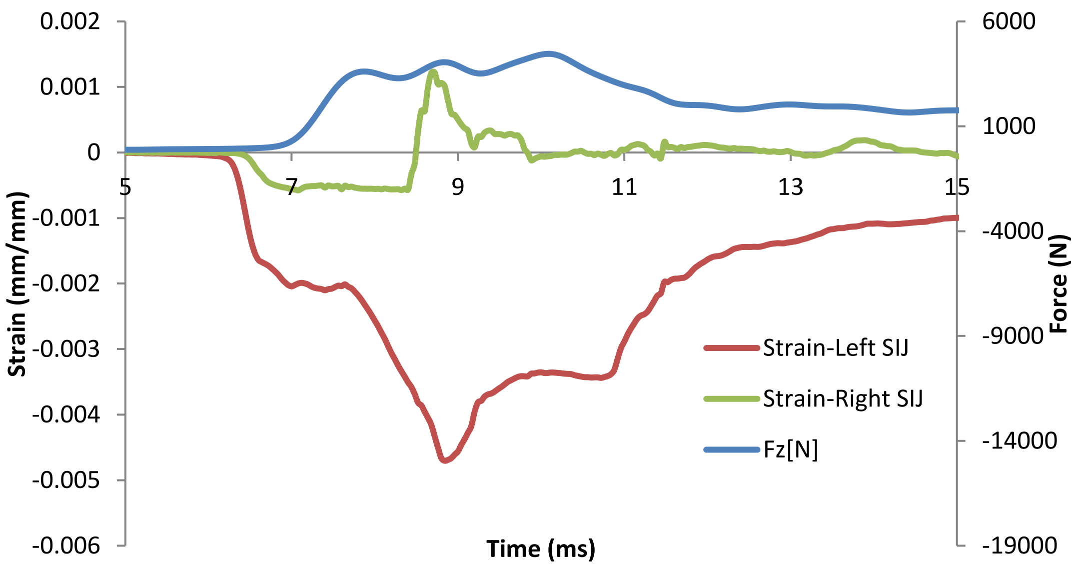
In this specimen, axial load with the PS divided also initiated a fractured neck of femur, as in Test 2, therefore strengthening the conclusion that pure axial load alone does not lead to an open pelvis. Therefore, in order to further simulate a potential flail mechanism, the anterior SIJ was divided to ascertain whether axial load is implicated at all in pelvic fracture, or are there other forces present.

Test 4: Sacrificed PS and Anterior Sacroiliac Ligament

In this test the PS and the anterior SIJ were divided prior to axial impact through the femur. This test resulted in maximum axial force of 4.5kN (Figure 7.26a,b). The PS was in tension (Figure 7.26b); while the left SIJ was fairly static, the right demonstrated compression (Figure 7.26c).



(a)



(b)

Figure 7.26: Test 4. Load at the spine, and strain gauge measurement at the pubic symphysis, and sacroiliac joints. Positive strain = tension, negative strain = compression.

The HSV captured what appeared to be a shear mechanism occurring at the PS at the white markers (Figure 7.27). The post-test CT in this specimen in this test demonstrated a ruptured left SIJ, with anterior and lateral displacement of the iliac wing, also seen on the HSV tracking the white markers. The femur remained intact in this test (Figure 7.28).

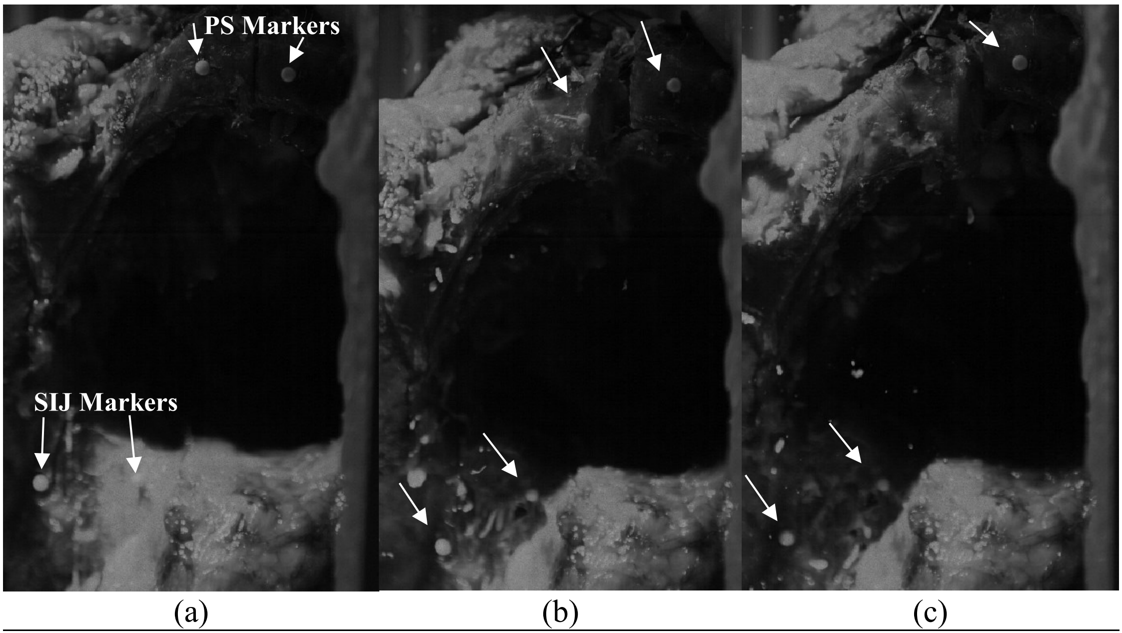


Figure 7.27: Test 4: HSV still images at the initiation, mid-point and final positions (2,4 and 8ms) demonstrating pelvic shear. Markers placed either side of the pubic symphysis and sacroiliac joints One pin was lost on the left side of the left pubic symphysis during the experiment.

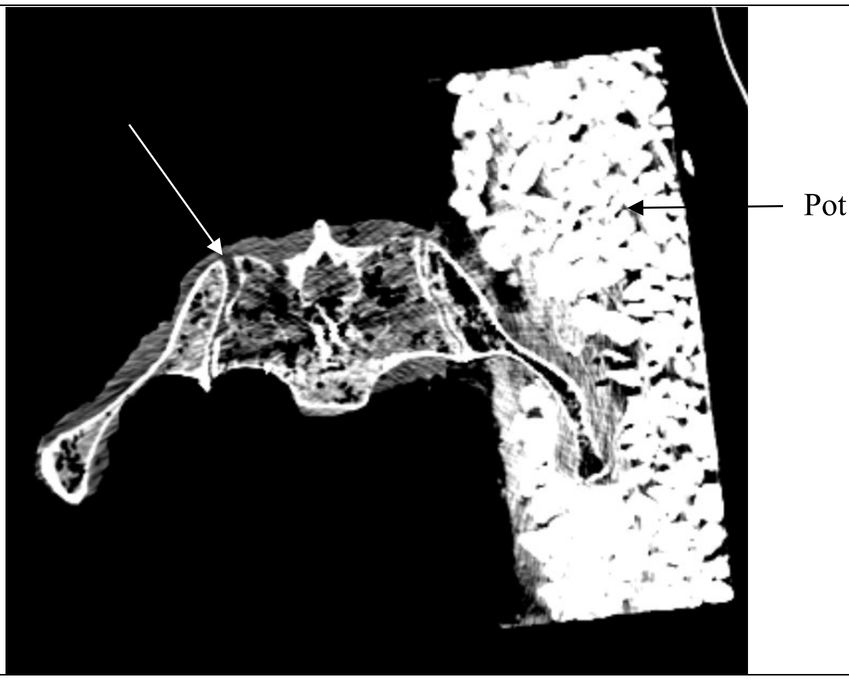
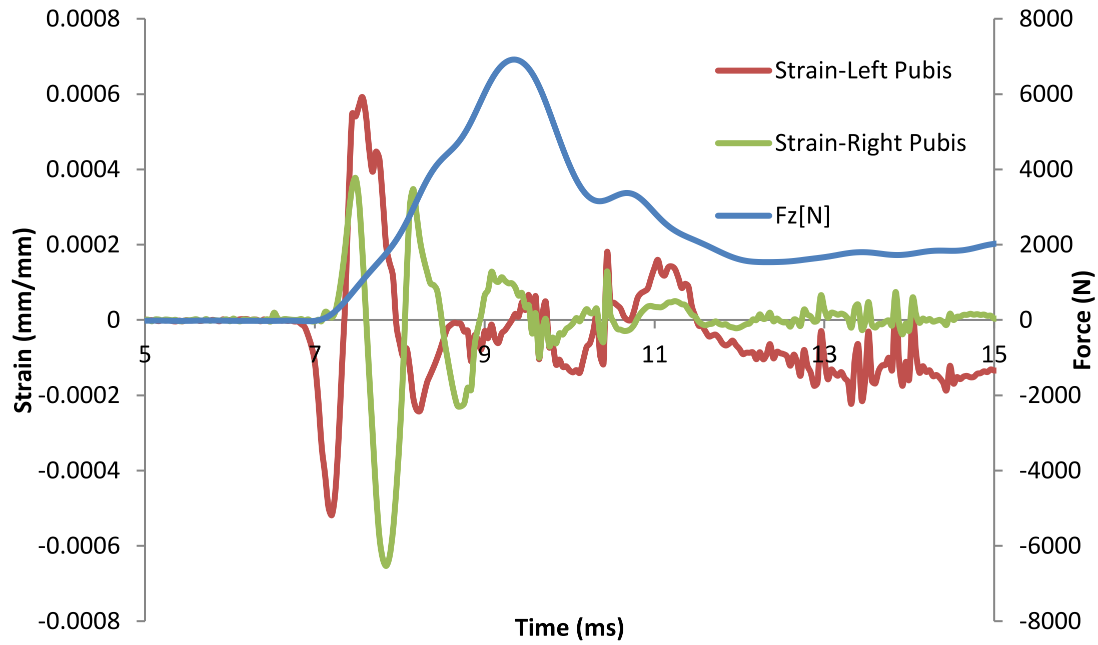


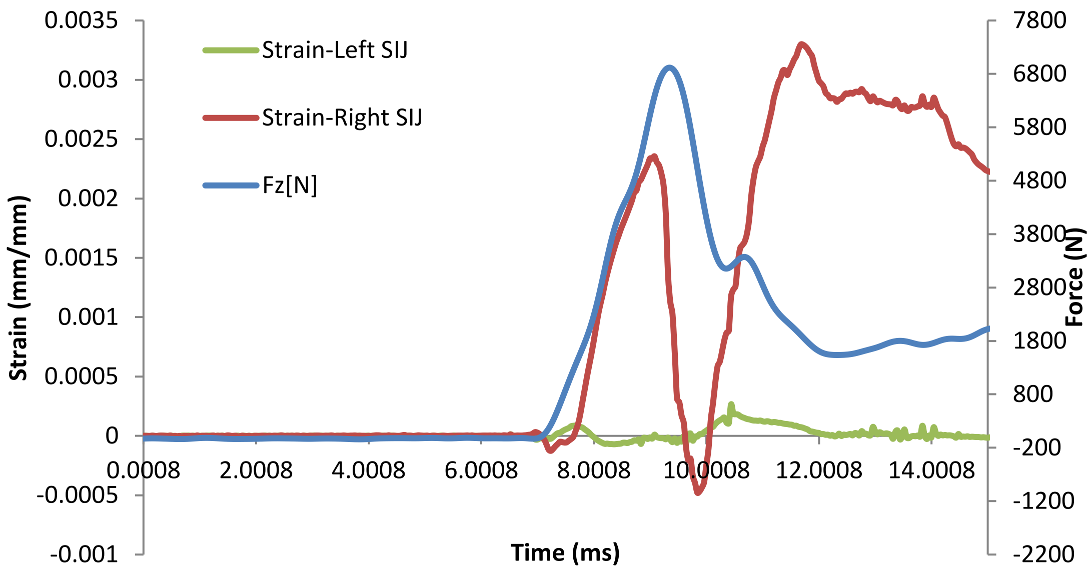
Figure 7.28: Test 4: Post-test axial CT scan demonstrating disruption of the left sacroiliac joint (arrowed).

Test 5: Sacrificed Pubic Symphysis and Anterior Sacroiliac Ligament

This test was repeated under the same conditions as Test 4, to assess the repeatability of the experiment. Therefore the PS and the anterior SIJ were again, divided. In this test, the peak load achieved was 6.9kN (Figure 7.29a,b). Strain at either side of the PS occurred in opposing directions, with tension at the right side, and compression at the left (Figure 7.29a). These opposing values could indicate shear. In the SIJs, the right side underwent a tension, with the left staying close to zero (Figure 7.29b).



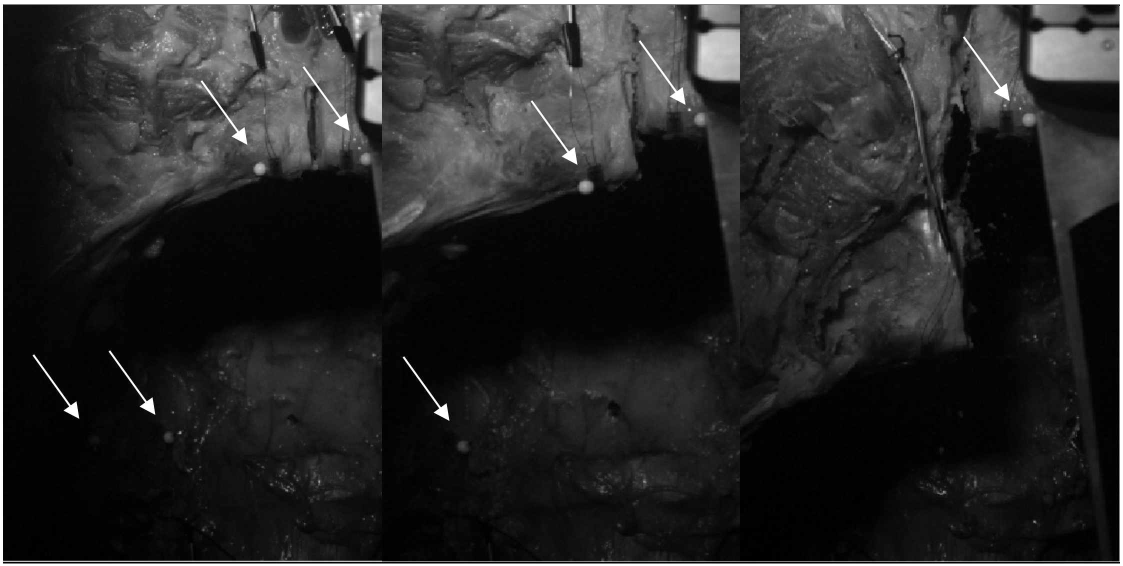
(a)



(b)

Figure 7.29: Test 5. Load at the spine, and strain gauge measurement at the PS, and sacroiliac joints. Positive strain = tension, negative strain = compression. (a) load and pubic symphysis strain gauges (b) load and sacroiliac joint strain gauges

The tracking of the markers in this test demonstrates a shearing effect of the PS and SIJ, with superior deflection of the left hemi pelvis on application of axial load (Figure 7.30). The post-test CT scans indicated a large disruption of the left SIJ (Figure 7.31). Corresponding widening of the PS is also depicted (Figure 7.31). This had been divided pre-test, however, further widening occurred during the test.



(a) (b) (c)

Figure 7.30: Test 5: HSV still images at the initiation, mid-point and final positions (2, 5 and 9ms) demonstrating gross shear of the sacroiliac joints and pubic symphysis. (a) left marker poorly visible in print (b) left marker off screen (c) both markers off screen.

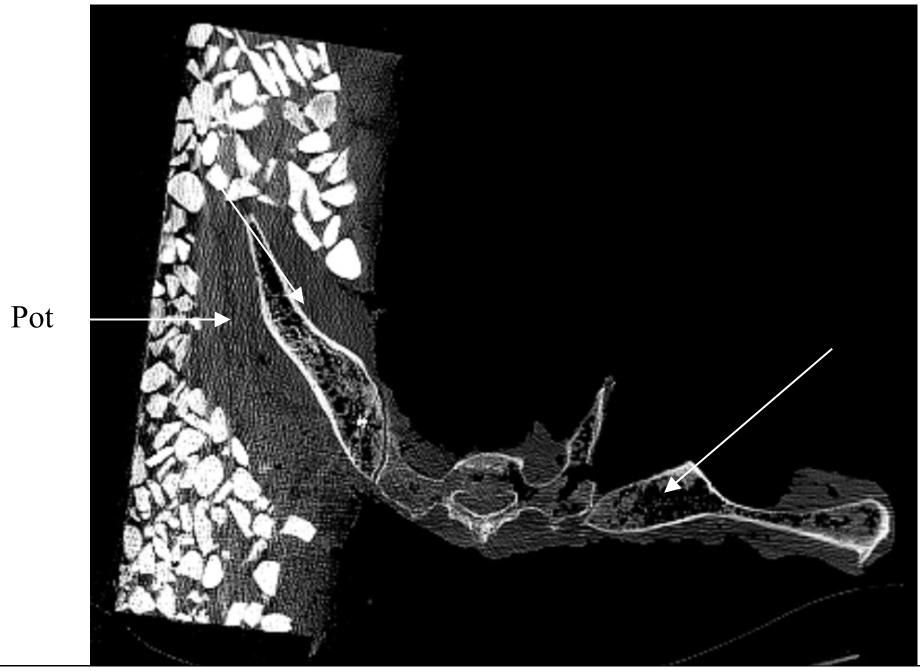


Figure 7.31: Axial CT scan of Test 5 demonstrating a disrupted left sacroiliac joint (arrow).

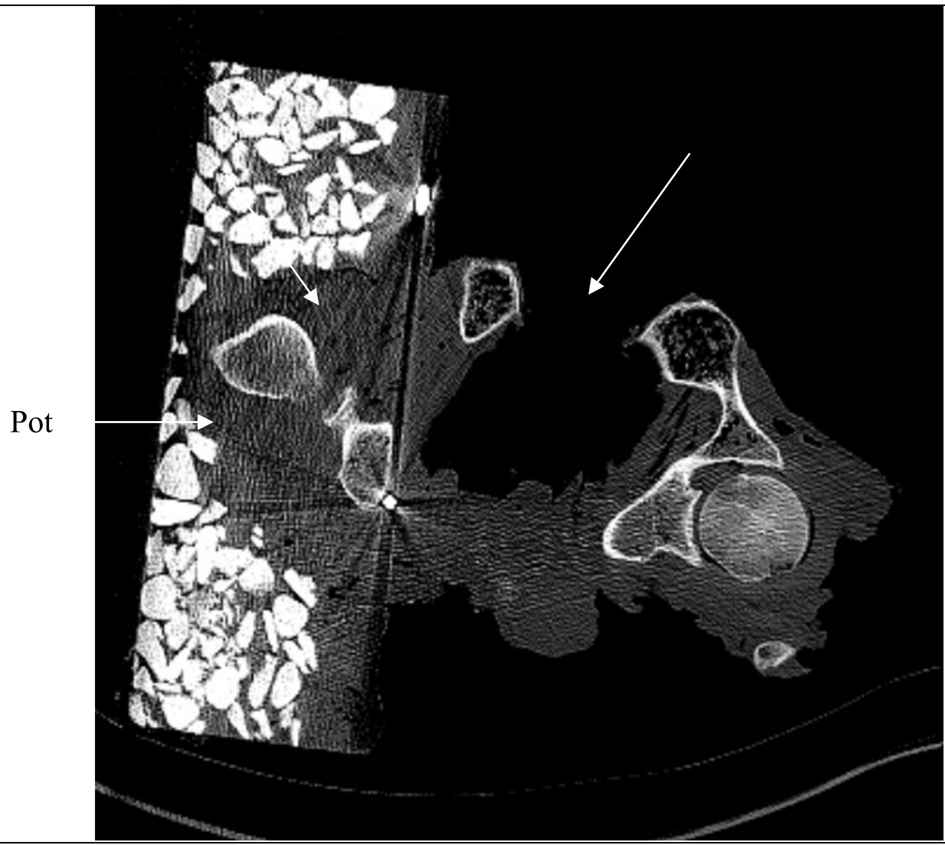


Figure 7.32: Axial CT scan of Test 5 demonstrating the pubic symphysis opening (arrow).

Summary of All Tests

The results of the strain gauges and load cell, as well as injuries sustained are presented in the following table (Table 5.1).

Test Number	Specimen No.	Pelvis Configuration	Peak Fz (kN)	Strain Gauge Left PS	Strain Gauge Right PS	Strain Gauge Left Side of Left SIJ	Strain Gauge Right Side of Left SIJ	Injuries on CT image
Test 1	04-15-0866	Intact	11.0	Compression	Compression	Compression then tension	Minimal	No Fracture
Test 2	16-09025	Intact	11.0	Zero	Tension	Tension-compression- tension	No data (lost)	Fracture Neck of Femur
Test 3	04-15-0866	Divided PS	3.0	Small compression remainder tension	Small compression remainder tension	All compression	Small Compression, large tension	Fracture Neck of Femur
Test 4	15-01015	Divided PS and Anterior Sacroiliac Ligament	4.5	All tens	Tension compression tension	Compression only	Compression- tens	Shear SIJ
Test 5	16-09014	Divided PS and Anterior Sacroiliac Ligament	6.9	Comp tens	Tension compression	Zero	Compression-tension	Shear SIJ

Table 7.3: Testing summary. Fz-Force in kN. SG-strain gauge, Fx-Fracture.

7.8 Discussion

This chapter presented for the first time a set of experiments on pure axial, impact load delivery through the femur to the pelvic complex simulating a blast injury when standing. This provides important initial evidence on the clinical outcome on pelvic integrity via medical imaging, deformation, and load transfer. With no previous studies that this can be compared to, it is difficult to assess the validity of the results. However, there have been some previous studies on load delivery in different directions, and on femoral positions based on automotive incidents, presenting different postures of the femur within the acetabulum.

Salzar et al (2009) demonstrated that in lateral acetabular loading, the pelvic load was much more evenly distributed, with equal load distribution at the PS and the SIJs, rather than loading purely at the ileum. This demonstrates the importance of the acetabulum for effective transfer of load delivery throughout the pelvic structures and minimising focussed loading and likely fracture. Yoganandan et al.(2001) reviewed pelvic injuries in relation to differing postures of the femur in flexion and extension, using a pendulum system, in which acetabular and proximal femoral fractures were noted. Building on this understanding, Rupp et al.(2003) performed a higher volume of testing; 33 tests on 25 cadavers on frontal loading at various femoral postures, flexion, extension, abduction and adduction, based on variations in seated postures within various vehicles. Flexed and adducted positions of the femur were found to reduce pelvic injury tolerance by 34 and 15% respectively compared with extended and abducted postures. Salzar et al (2007) also reviewed various femoral postures and the effect on pelvic injury, and found that the flexed and abducted posture of the femur lead to higher loading rates through the pelvis, with a greater chance of pelvic injury than in extended and adducted positions. The position of the femur within the acetabulum clearly influences pelvic fracture patterns.

The proposed mechanism of axial load due to blast could also be compared with data on falls from height, specifically, purposeful falls, where the casualty falls feet first as opposed to accidental where the casualty tends to rotate and injure the proximal body regions such as head and chest (Bruno et al. 2014). Therefore, there could be some comparison to be made with falls data, and blast pelvic biomechanics, and could also provide data on load transfer via the femora in the standing position.

It is well known that the higher the fall distance, the more severe the injuries sustained (Bertocci et al. 2004), and this could be compared with the velocities the femur is driven into the acetabulum in blast insults. The chance of fatal injuries is directly related to the height of the fall in both adults and children. In children, fatality is quoted as 3 storeys (9m) or less sustaining a 100% survival, and 50% survival between 5th and 6th storey (15-18m) falls (Barlow et al. 1983). In a study on falls in adults, 15m was the median fall height in fatalities (Dickinson et al. 2012). In fall from height studies, the characteristics of the floor surface of impact has an effect on injury types seen, and this could be similar to blast axial loading in the dismounted soldier, where surface characteristics may be variable (i.e. soil rigidity, or the presence of solid fragments, or a solid surface) (Bertocci et al. 2004). A study of 300 purposeful falls from height demonstrated SIJ and PS injury to be significantly higher in incidence with higher falls (>12m) and not an injury that occurs at lower fall levels (Bruno et al. 2014). The high incidence of pelvic injuries in greater heights of fall is also noted in additional studies (Hahn et al. 1995), but without the specifics of pelvic injury pattern. This confirms the association of pelvic injury with predominantly high rate loading, as presented in Chapter 4.

Neck of femur fracture, as occurred in the experiments in this research, is well documented in lateral falls from standing height, particularly in the elderly with low bone mineral density (Center et al. 1998; Parkkari et al. 1999), however, the presence of femoral neck fracture is not widely reported in the literature in fall from height analyses. The large study by Bruno et al (2014) only contains 'thigh' and 'hip' as injury categories, and the injury specifics, such as if this is bony or soft tissue injury, or where exactly this injury has occurred, is not included. Therefore, the findings of Bruno et al (2014) cannot be compared with the experiments in this research as to whether neck of femur fracture is a common feature in high rate axial loading of the lower limb.

There are biomechanical studies on fall velocity on falling from standing focusing on hip fractures in the elderly (van den Kroonenberg, Hayes, and McMahon 1996), and in paediatric falls focussing on head injury (Ibrahim and Margulies 2010), but less studies on falls from greater heights. For the purposes of forensic investigation, numerical simulations have aimed at assessing the kinematics of the fallen casualty, but these have not been performed on a large scale, and are based on replicating the event using bystander sightings and correlating injury patterns. Numerical simulations therefore cannot be used independently to assess accurately potential injuries under axial load, due to the subjective nature of the bystander observations (Adamec et al. 2010). Therefore, there is little data to date within the body of literature that is helpful to correlate with axial load to the pelvis in standing postures in relation to blast injuries.

7.9 Limitations

There are inherent limitations with any reproduction of injury pattern. Although every reasonable attempt has been made to mitigate these limitations, they are presented below.

Specimens

Specimen availability was an unavoidable limitation, as there is only a finite number of pelvises that could be available within this study's timeframe. There are natural variations within the anatomy, and bone density, which may lead to differences between the behaviour of specimens. The specimens were requested to be below the age of 60 years, to replicate male soldiers as closely as possible. However, this is clearly above the average age of a military soldier at 35 years (Lolita Burrell et al. 2003). In addition, there is limited availability of cadavers with an absence of skeletal pathology and communicable diseases, and even more so at younger age groups. It would have been difficult to have received younger cadavers at similar ages to the soldiers, therefore cadavers were used with a balance between their age, and the ability of the supplier to provide them. Nevertheless, this is unlikely to have been a significant factor, as the below figure presents the ages of 60 in males, and there has been shown to be minimal difference in bone mineral density between the ages of 20 and 60 (Figure 7.33).

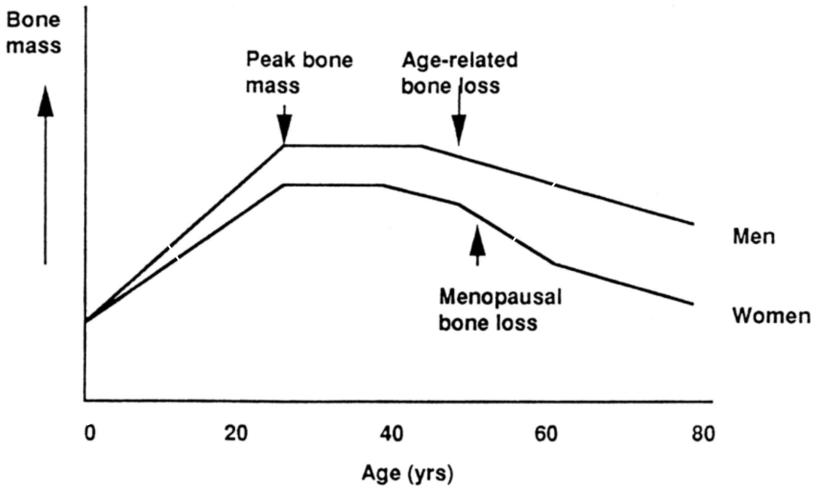


Figure 7.33: Bone mass age related changes in males and females (Compston 2001).

Only male pelvises were selected, due to the clinical dataset being 100% male. This is clearly a limitation of the entire research project, as the anatomy of the female pelvis is different to the male in shape (Young and Ince 1940), and even the behaviour under stresses and strains is likely to be different due to oestrogen dependent ligament laxity for the purposes of permitting PS and SIJ opening in childbirth (Damen et al. 2001; Lewis 2000). With the changes to operational policy with regards to permitting female soldiers into front line service, this is an important factor that must be considered in this anatomical region and others, to ensure personnel protective equipment is as suited to the female as it is the male anatomy (The Guardian 2016).

Experimental Set-up

The test protocol presented here was developed to create a scenario with as realistic boundary conditions as possible taking into account the posture of the pelvis. A great deal of care was taken to position the pelvis, spine, and hemipelvis in anatomically correct positions. The fixation of the specimen upon the load cell, and therefore the floor beneath, offers more resistance than would occur in the real blast casualty due to inertial forces propelling the body proximally against less resistance (in the dismounted casualty). This is a difficult problem to overcome, and would involve a different experimental set up. Sled mechanisms that have been utilised for seated blast tests could be used for dismounted tests, with corresponding torso weights added, or even full body testing. This is a mechanism that can be considered in future work. In addition, the posture of the femur may be variable in the operational scenario, with a flexed femur as the device is encountered. Variations in the position of the femur will be addressed in further work (section 8.9).

Instrumentation

Strain gauges are designed to be placed on a flat, clean, dry surface. Although care was taken to place them on clean bone and on a flat portion of the pelvis, the PS and SIJs exert natural curvature, and tissue is often adherent and difficult to completely remove. Therefore, strain-gauge data is not a perfect, representation of deformation, however, can be used as a guide. Due to the high rate testing performed, one gauge was lost during testing (test 2, right SIJ gauge). In addition, one of the markers was separated from the pelvis during one test, and therefore could not be used. The load cell information is useful for understanding load transfer into the spine, and therefore relative absorption at the pelvis, however, the additional load pathway created by the pelvic pot could have directed through the contralateral ilium some of the load applied to the floor, giving an underestimate of load transfer at the spinal pot. This could be mitigated in future tests by attempting to apply a load cell beneath the hemipelvic pot.

7.10 Future Work

Finite Element Analysis

In order to acquire a more comprehensive understanding of the biomechanics of the pelvis when load is applied through the femur, the experimental data from here may be combined with computational efforts. It would be useful to analyse further the experiments presented here but also to perform multiple ‘tests’ of different postures, loads, and velocities without the resource of a cadaver. Multiple simulations could reproduce a greater variety of loading configurations, which could help inform future pelvic physical testing when more cadavers become available. Therefore, an FE model of this experiment was developed that will be presented in the following chapter.

Physical testing

This set of tests has helped to understand how axial load delivered through the lower extremity affects the pelvis. These tests have provided important evidence to suggest that the axial load alone will preferentially break the femoral neck, before PI occurs. When the front of the pelvis has failed, axial load can lead to pelvic shear without femoral neck fracture, suggesting the integrity of the front of the pelvis is key to separation at the posterior pelvis, in which disruption can lead to catastrophic vascular injury. Further answers are required to further understand dismounted blast pelvic disruption, and these could be addressed with additional testing when more cadaveric specimens become available:

a. Do different speeds and loads lead to different types of pelvic and femoral fractures in axial loading?
b. Does the angle of the femur make a difference to injury patterns at both the femur and pelvis in axial load?
c. What is the injury tolerance of the PS at high rate loading?
d. What is the mechanism of PS failure in blast?
e. How could PS opening be mitigated in blast injury?

Therefore, further testing will be performed in future work to continue to understand this important injury pattern. The implications of this work will be shared with the Lower Extremity Personnel Protective Equipment Working Group at Defence Equipment and Security, MOD Abbeywood.

7.11 Conclusions

This work adds the following information to the knowledge of dismounted blast pelvic injury

a. Axial load alone is unlikely to shear the SIJs if the PS is intact;

b. If the PS has failed, then axial load alone may fail the SIJs;

c. The intact PS may help prevent shear;

d. Pure axial load preferentially breaks the femur; therefore, a femoral neck fracture may be an indicator of pure axial load in the dismounted soldier.

Building on the understanding developed in this and the previous chapter on injuries to the pelvis in a standing posture in blast, the following chapter will present two FEA models. The first is a model in which this experiment is replicated and further variations of loading direction via the acetabulum are presented. The second is a model of the human pelvis with associated vasculature. This model will provide an insight into the biomechanical behaviour of vessels within the pelvis as the bones deform, and will help understand how vascular injury occurs in the disrupted pelvis. To help understand how it could ultimately be mitigated to potentially save lives from major haemorrhage.

CHAPTER 8

DEVELOPMENT OF A FINITE ELEMENT MODEL OF THE PELVIS AND VASCULATURE

Chapter 6 presented methods for assessing pelvic joint separation using radiographs, and correlating this with vascular injury. However, one of the main limitations of this study was the inability to assess multiple deformation planes simultaneously. Chapter 7 presented an experimental technique aimed at applying axial load to the pelvis in standing posture to assess pelvic response, which provided strain and injury data, as well as insight into dynamic pelvic movement in axial loading. This chapter uses this information, as well as the incident data in Chapter 5, to develop two finite element (FE) models. The first FE model is of the bony pelvis with vasculature to further assess the relation between pelvic joint separation and vascular injury. The second FE model reproduces the experimental conditions of Chapter 7, in order to provide further insight into the mechanism of injury of the pelvis under axial load and investigate additional loading scenarios relevant to an explosive insult in the open.

8.1 Finite Element Analysis

8.1.1 Introduction

Finite element analysis (FEA) enables computerised mechanical testing on a variety of structures of known material properties under a variety of loading conditions. FEA is a mathematical technique, which involves the simplification of these complex situations into a finite number of discrete, smaller problems. These can be individually solved and combined to create a complete picture of the behaviour of a structure under selected conditions. It works by subdividing complex geometries such as skeletal structures into small individual shapes: triangles in 2 dimensions, or tetrahedrals in 3 dimensions. This is a procedure known as 'meshing.' A large set of equations can then be set up that is solved by accounting for the contributions of each one of the individual elements. These individual elements are connected to one another at specified points known as 'nodes', which allow the information on deformation and loading to be shared, and therefore these individual contributions to be 'stitched up' to produce a global solution for the whole structure.

FEA has the advantage of the ability to perform multiple tests under multiple conditions much more quickly than an equivalent number of physical tests, and without the use of consumables, meaning that FEA is cost effective compared with physical testing. Although FEA uses known material properties gleaned from physical experimentation either performed by the individual, or from the literature, some values are not known, or must be estimated. Therefore, FEA can be considered as providing an as reasonable as possible estimate of values with the information available, but be accepted with an understanding of the inherent limitations. FEA often guides the focus of experimental testing, providing a framework in which to guide physical experiments. This enables experiments to be focussed from the outset, and avoids wastage of materials.

The steps to develop a finite element model that represents as accurately as possible the behaviour of the anatomical structure is shown in Figure 8.1.

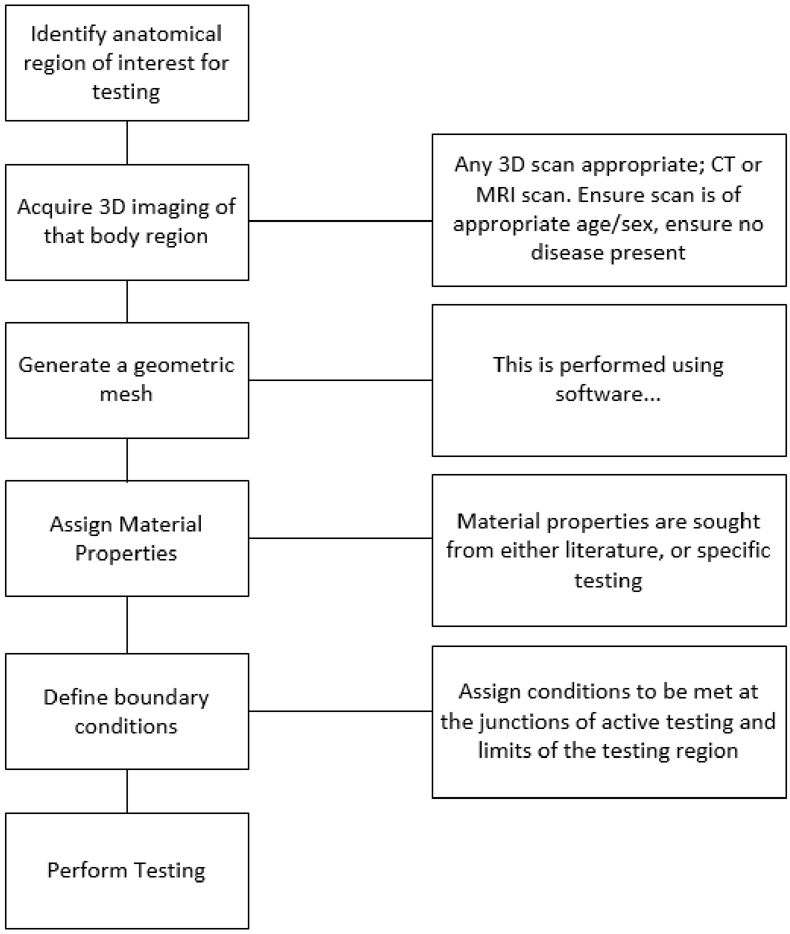


Figure 8.1: Criteria and sequence of events in creating a finite element model to use in an analysis.

FE models exist throughout the relevant literature and in medical practice. They are tailored to answer specific desired clinical problems, for example, testing the load required to cause fractures in particular directions in long bones, assessing geometry and variability for surgical implants, and predicting injury patterns in human tissues.

8.1.2 Existing FE Models of the Human Pelvis

As presented in Chapter 4, the pelvic ring is a complex biomechanical structure, made up of a network of interlinking bones and ligaments which are comprised of a fairly sophisticated architecture. Therefore, FEA of this structure can provide useful insight on load transfer during normal activities and indeed during injury, where physical testing can prove difficult. Early representations of the pelvic bones were an important step in developing pelvic models, but are rather oversimplified by modern standards. The first FE pelvic models were created in 1982 in two dimensional (2D) form to aid in the design of acetabular prostheses (Carter, Vasu, and Harris 1982; Vasu, Carter, and Harris 1982). Additional semi three dimensional (3D) but axisymmetric models were also created at that time for a similar purpose, to design components for total hip arthroplasty (Hulskes 1987; Pedersen et al. 1982). With these early models, the 2D models fail to account for the entire acetabular surface, and subsequently overestimate flexibility, whilst the semi 3D axisymmetric models underestimate flexibility as they assume an intact acetabular wall through the 360° surface, and therefore overestimate actual stiffness in this region (Dalstra 1995). Later models recreated the geometry from CT scanning, and therefore could represent more accurate anatomy (Figure 8.2).

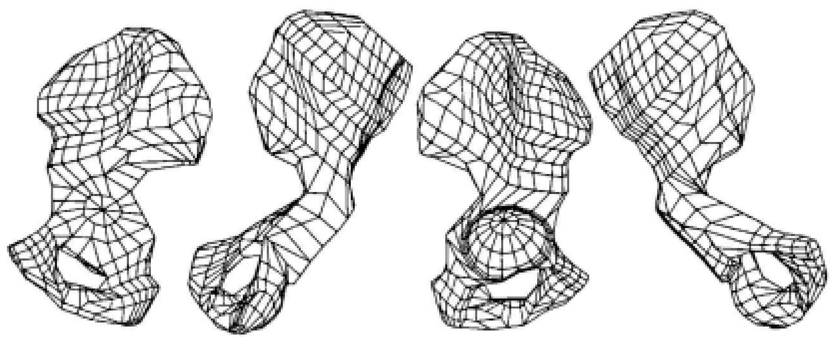


Figure 8.2: FE image of a pelvic bone mesh. Adapted from (Dalstra 1995).

Vavelle et al (2013) describe the creation of a whole body FE for the purpose of injury modelling, and validation with cadaveric sled and drop tower testing, to assess lateral impacts. The thoracic and abdominal regions in this study were reported to be a good match in terms of reliability between the model and cadaveric testing, however the pelvic FE overestimated the pelvic stiffness in these studies. The remainder of pelvic FE studies are aimed at assessing intervention after fracture (García et al. 2000), or for implant selection (Dopico-González, New, and Browne 2010; Huiskes and Chao 1983; Watanabe et al. 2000). There are no FE models in existence representing the human pelvis in response to blast loading, and none representing the human pelvis and accompanying vasculature.

8.1.3 Existing FE Models of Vasculature

Existing FE models of human vasculature exist for various purposes: to understand the structure and function of vessels under both normal and pathological conditions, for example aneurysmal disease and atherosclerosis, and to aid in the development of medical devices like vascular stents and grafts (American Society of Mechanical Engineers. et al. 1977; Lei et al. 2001). The development of an FE model of the vessels requires an initial approximation of the material properties of the vessels. Soft biological tissues, including blood vessels, contain both collagen and elastin as their two primary load bearing structures. Elastin is a compliant material, whereas collagen is much stiffer (Dobrin and Mrkvicka 2016). In the unloaded state, within soft tissue, elastin fibres are taught and collagen tortuous and furrowed, and therefore, when relaxed, elastin fibres bear the majority of the load applied to the tissue.

There are inherent difficulties with the procedures used to establish these material properties, which is key for accurate FEA. Testing live subjects is challenging, as the majority of testing mechanisms require invasive monitoring, which can produce significant morbidity, and would be unlikely to pass an ethical approval process, particularly in humans. Live animal models can be utilised, however there will be differences between human and animal tissues. It is also well known that the material properties of in vivo and in vitro blood vessels differ, therefore testing in vitro blood vessels provides important information, however these differences must be acknowledged. Therefore, establishing a fair and accurate representation of the material properties of human blood vessels could only be obtained by an accumulation of knowledge provided by live animal, and in vitro human studies.

To the author's knowledge, there are no existing FEA systems described in the literature focussing on traumatic vascular injury, nor are there studies relating to the pelvic vasculature specifically and certainly not in situ within the bony structure of the pelvis. Therefore the model developed here is the first of its kind to model vascular trauma, and the first to replicate this in the context of pelvic arterial trauma.

8.2 Aim

From the clinical data it has been established that the pelvis disrupted at the posterior pelvis (at the SIJs) is most often associated with vascular injury, and this most often occurs in soldiers on foot at the time of the blast insult. The measurement method in Chapter 6 demonstrated the relation of three planes of disruption to the presence or absence of vascular injury. Chapter 7 tested axial load in the standing pelvic posture, and found that pure axial load alone is unlikely to cause disruption at the posterior pelvis, suggesting that additional forces must be implicated. The aim of this chapter, therefore, was to use FEA to address the remaining questions from Chapters 6 and 7:

a. Use FEA of the vasculature within the pelvis to identify key areas of the arterial network vulnerable to rupture, in pelvic bony injuries encountered in blast;
b. Reproduce the conditions of the experiment presented in Chapter 7 in FEA, testing the effects of axial load through the femur to pelvic deformation;

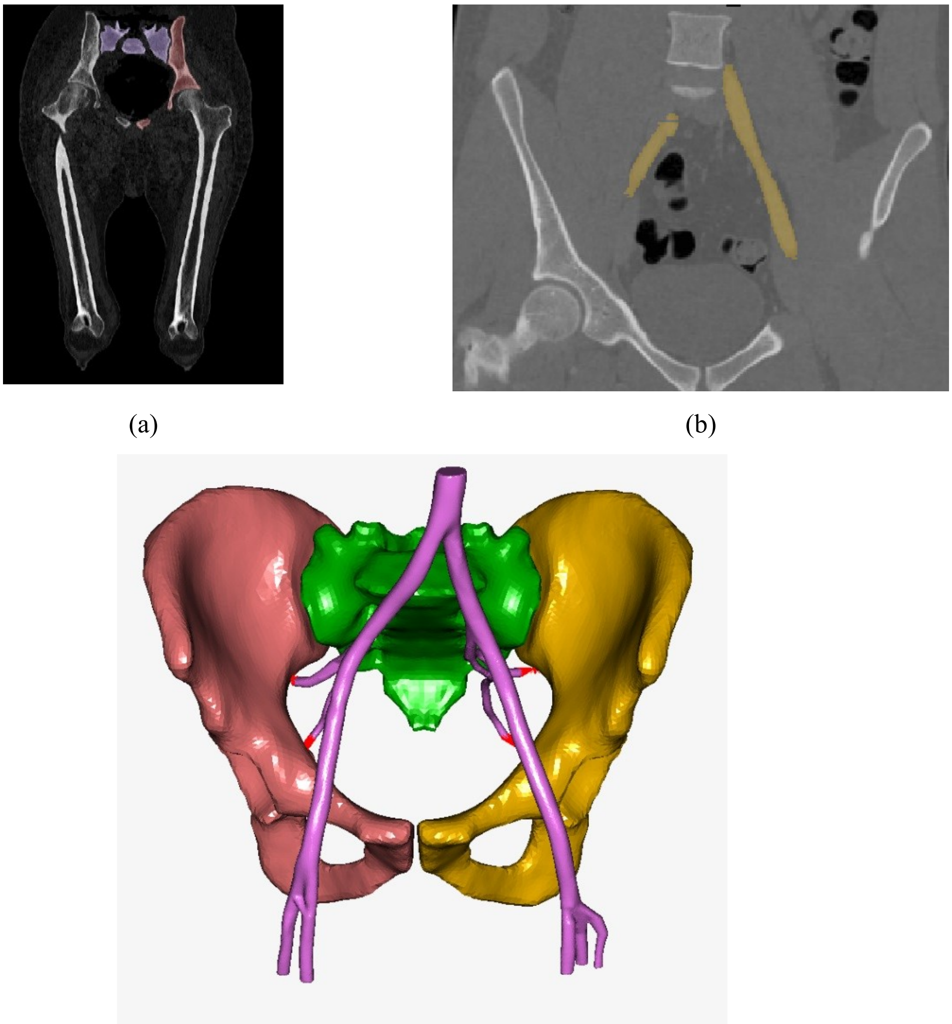
c. Use the model above to reproduce additional loading pathways through the lower extremity that could lead to pelvic injuries seen in blast trauma

Both techniques will help in the understanding of injury mechanisms in the blast pelvis, both in terms of underlying vascular injury, and load transfer in axial loading in varying directions. Importantly, this will help understand how these injuries can be mitigated by opposing forces likely to lead to major vascular injury and potential fatalities. As explained in Section 8.1, developing an FE model entails selecting the anatomical region for testing, reproducing the geometry, assigning material properties, and imposing boundary conditions. This was performed for these two FE models, with some key differences due to the overall differing aims of the studies. For the purposes of this thesis, despite that the phenomena in question are dynamic, static FE models were developed. Static models, whereby the mechanical response of the structure in question under a maximum load or displacement is of interest, were deemed appropriate to answer the research questions of this thesis within a realistic and useable timeframe. The models presented in this chapter were developed with Dr Diagarajen Carpanen, Research Associate within the Royal British Legion Centre for Blast Injury Studies at Imperial College London at the time of writing.

8.3 Part 1: A Pelvic FE Model with Vasculature

8.3.1 Geometry and Mesh Generation

To obtain the initial pelvic geometry for the FEA, DICOM images of a CT angiogram of a 23-year-old male pelvis was obtained, and the data was imported into Mimics V16 (Materialise, Leuven, Belgium) medical imaging software. Surface geometries of the ilium, sacrum and arteries were generated through the segmentation process (Figure 8.3), which isolates the required regions for testing. The geometries were imported as stereo-lithography files to Geomagic Design X (3D Systems, USA) to create solid objects suitable for meshing in Hypermesh (v14, Altair Engineering, USA). The bones were modelled as rigid non-deformable bodies to reduce computational run time, while the artery was meshed with 4-noded tetrahedral elements. The simulations were performed in FE software package MSC Marc (v2016, MSC.Software, USA).



(a) (b)

(c)

Figure 8.3: CT scans used to identify pelvic surface geometry for FEA (a) identification of bony outline (b) identification of vessel outline (c) final reconstruction of the FE model.

8.3.2 Material Properties of the Iliac Artery

The material properties of arteries and veins are key to their function, to maintaining the flow and pressure of circulating blood volume. Their properties determine the pressure-flow relationship of these vessels, the speed of pulse waves, and stress-strain relations of vessel walls (Lehoux, Castier, and Tedgui 2006). There were no previous studies identified describing the material properties of the iliac arteries, therefore, the properties of the abdominal aorta were selected due to the relative similarity in position and calibre compared to vessels in other anatomical regions (Humphrey and Holzapfel 2012). The iliac artery was modelled as a homogenous incompressible linearly isotropic elastic structure with a Young's modulus of 2.2 MPa and a Poisson's ratio of 0.45 (Bergel 1961). For the purposes of this model, the bony structures were assumed rigid (i.e. non deformable) as their Young's modulus – which is a measure of stiffness – is 5 orders of magnitude greater than that of the vessels (20,000MPa *vs*. 2.2 MPa), and therefore any bony deformation due to vascular stretch would be negligible.

8.3.3 Boundary Conditions

The fixation of the vessels within the pelvic bones in the model was important to model as accurately as possible, as inaccuracies could lead to unnatural behaviour of the model. The vessels were therefore fixed to the pelvic bones at the posterior pelvis, in a manner simulating the fixation from the retroperitoneum and surrounding connective tissues. At the distal free ends of the vessel, fixation was performed in space to mirror the behaviour of the fixation of the distal vessel, for example, in the lower leg at the continuation of the external iliac portion of the pelvic vasculature. The left hemipelvis and sacrum were fixed in all degrees of freedom, and the right hemipelvis was able to move as the simulation required.

8.3.4 Applied pelvic displacements

The joint displacements presented in Chapter 6 were only presented in single planes, and did not take into account combinations of injury. In order to address this limitation in this FEA, combinations of different disruptions were used. The following tables present the 5 directions of joint separation, and their relationship to other direction of separation, as both average and maximal values (Table 8.1), and as a percentage of additional planes disrupted in the 5 different planes (Table 8.2).

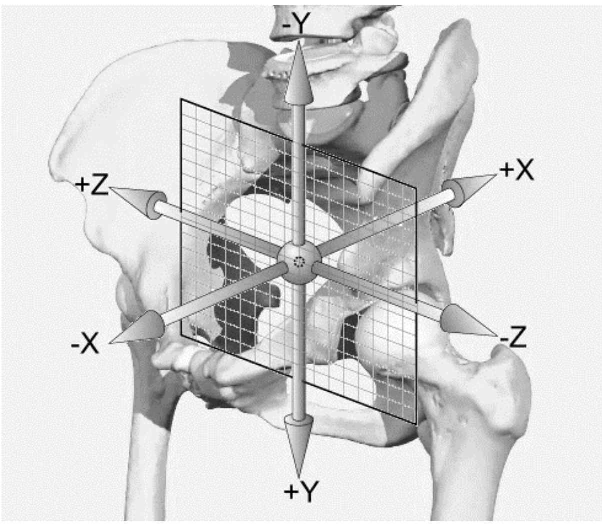
Disruption distances (mm)	Superior	Inferior	Anterior	Posterior	Lateral
Superior	8(16)	n/a	12(21)	4(4)	11(16)
Inferior	n/a	8(33)	26(40)	3(4)	7(16)
Anterior	9(16)	11(13)	10(40)	n/a	12(30)
Posterior	8(12)	13(33)	n/a	5(18)	9(16)
Lateral	9(16)	8(33)	10(40)	5(18)	9(20)

Table 8.1: The relationship between distances in different planes. Values are averages, with maximum distances in brackets. Major outliers have been removed.

	Superior	Inferior	Anterior	Posterior	Lateral
Superior		n/a	62%	23%	100%
Inferior	n/a		18%	27%	100%
Anterior	44%	11%		n/a	100%
Posterior	20%	20%	n/a		100%
Lateral	10%	10%	19%	17%	

Table 8.2: The relationship between distances in different planes (percent). Major outliers have been removed.

Realistic displacements of the pelvis based on the above values were applied (Table 8.3). These were based on the measurements correlating with the median distances of separation required to cause vascular injury in all planes. The planes are represented by the figure and table below (Figure 8.4).



Equivalent displacements	
+x	Posterior
-x	Anterior
+y	Inferior
-y	Superior
+z	Lateral
-z	

Figure 8.4: Pelvic disruption planes and equivalent pelvic movement directions for the vascular FEA. +x=posterior, -x=anterior, +y=inferior, -y=superior, +z=lateral.

Removing outliers, the maximum displacement distances were chosen as 20 mm in all planes (Table 8.3). This resulted in 10 simulations that were run.

	Displacement (mm)		
Model	x	y	z
M1	0	0	10
M2	0	0	20
M3	5	10	10
M4	10	20	20
M5	5	-10	10
M6	10	-20	20
M7	-7.5	10	10
M8	-15	20	20
M9	-7.5	-10	10
M10	-15	-20	20

Table 8.3: The displacements in each plane gleaned from Chapter 6 data, and used to inform realistic movement patterns of the hemipelvis in the FE simulations. +x=posterior, -x=anterior, +y=inferior, -y=superior, +z=lateral.

8.3.5 Results

The results of the analysis are presented in Table 8.4, where the movement of the pelvis is described in the three planes, and the stress and strain data presented, in order to make predictions on the likelihood of vascular injury in particular locations of the vessel (Figure 8.5).

	X (mm)	Y (mm)	Z (mm)	Maximum Equivalent Stress	Maximum Equivalent Strain	Location
M1	0	0	10	0.135	0.061	a
M2	0	0	20	0.31	0.139	a
M3	5	10	10	0.38	0.172	a
M4	10	20	20	0.68	0.32	a,c
M5	5	-10	10	0.038	0.017	a
M6	10	-20	20	0.11	0.049	a
M7	-7.5	10	10	0.28	0.128	a
M8	-15	20	20	0.57	0.26	a
M9	-7.5	-10	10	0.081	0.036	b
M10	-15	-20	20	0.112	0.05	b,c

Table 8.4: FEA disruption distances, and stress and strain data of the vessels in anatomical locations. +x=posterior, -x=anterior, +y=inferior, -y=superior, +z=lateral. The location column is with reference to Figure 8.5.

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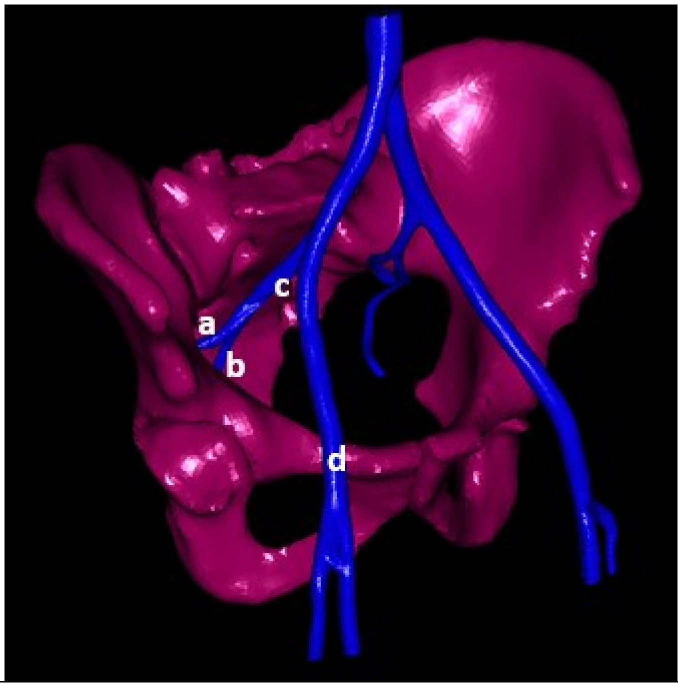
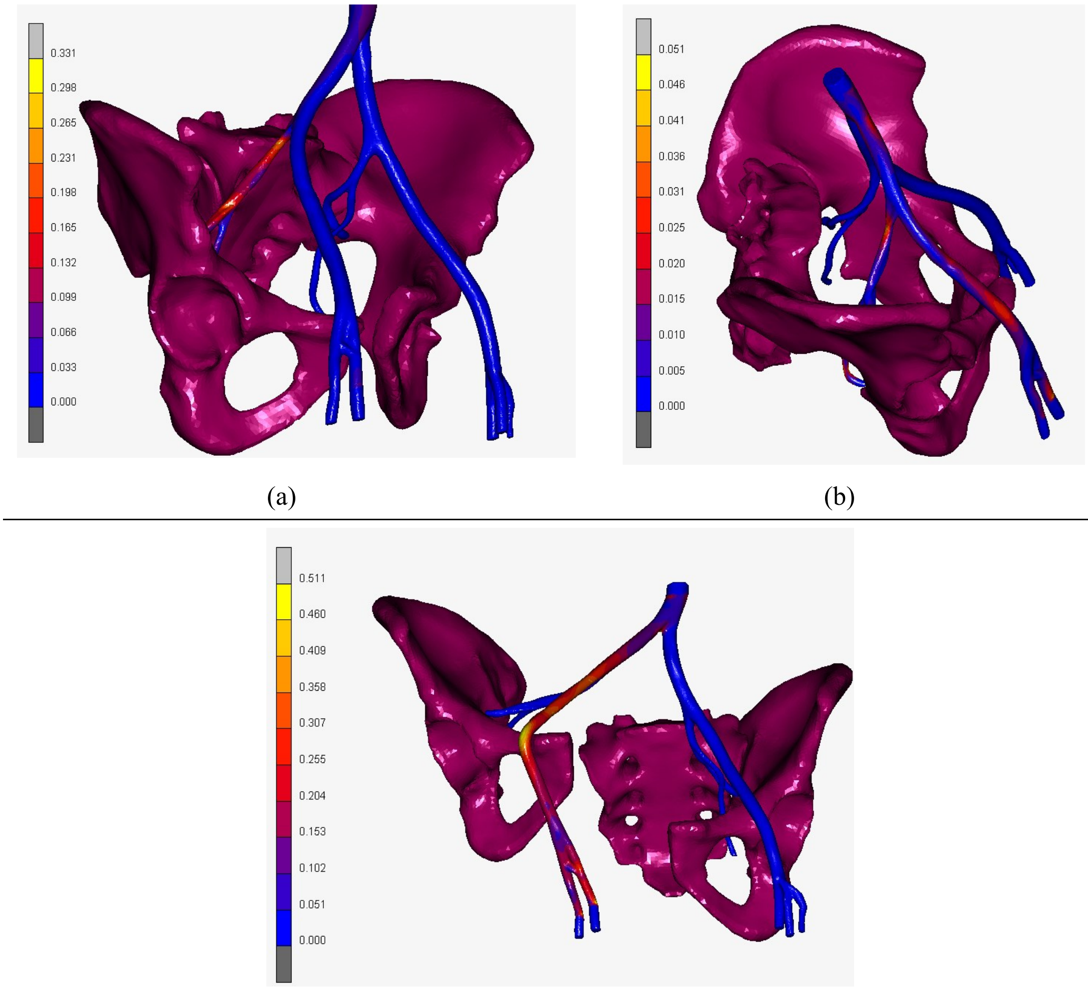


Figure 8.5: FEA of pelvic vessels demonstrating the areas of maximal strain in the vessels in movement of the hemipelvis in selected directions. a=posterior division of internal iliac, b=anterior division of internal iliac, c=bifurcation of common iliac artery, d=external iliac/femoral artery junction.

This model identifies key points of stress and strain concentrations that occur at the arterial tree upon pelvic displacement, which make vessels vulnerable to rupture. From the literature we can ascertain that failure of the aorta occurs at 0.3-0.8MPa, at 50-100% strain (Humphrey and Holzapfel 2012). Values for the iliac artery are not known, which is a limitation of this study, however, it is reasonable to assume that values would be similar. If failure occurs at these stress values, then any value over 0.3 MPa may be assumed to cause vascular injury. These areas where increased stresses and strain occur are labelled on the diagram (a-d), as posterior division of internal iliac, anterior division of internal iliac, internal iliac proper, and the transition between the external iliac and femoral artery respectively. Area (a), the posterior division of the internal iliac, demonstrates the highest stresses in all planes of injury (Figure 8.5). Area (b) is implicated in simulations M9 and M10, which corresponds to anterior, lateral and superior displacement. Area (c) is implicated in M4 (inferior, lateral and posterior displacement) (Figure 8.6a) and M10 (anterior, lateral and superior displacement)(Figure 8.6b). Stresses and strain to area (d) is implicated only when displacements reach over 100mm in all planes (Figure 8.6c). Therefore the external iliac/femoral injuries noted in Chapter 5 can only be due to bony disruption in extreme pelvic opening. If extreme pelvic opening has not occurred, then there must be an additional mechanism occurring to lead to disruption in this area.



(c)

Figure 8.6: Pelvic arterial strain on movement of the hemipelvis, in simulations (a) M4 (posterior, lateral, and superior displacement) (b) M10 (anterior, lateral and superior displacement) and (c) a maximal displacement at 100mm in all planes.

This information is very important when considering protection against arterial injury. This data identifies key areas, and the planes of disruption in which they occur:

the division of the common iliac artery, the division of the internal iliac artery, and the external iliac artery as it crosses the pelvic brim as areas prone to rupture.

8.4 Part 2: An FE Model of the Pelvis under load

The development of this second FE model follows on from the experiments in Chapter 7 to reproduce the loading conditions of the experiments, and other potential loading scenarios pertinent to a flail injury mechanism due to an explosive insult to a dismounted soldier.

8.4.1 Geometries and Meshing

The geometry of the pelvis was obtained as described in section 8.3.1. The pelvic arteries were omitted since this tissue was removed from the cadaveric experiments. The bones were meshed with 4-noded tetrahedral elements as shown in Figure 8.7. The ligaments at SIJ and PS were modelled with spring elements since it is impossible to get the geometry of ligaments from CT scans, and it would be computationally expensive to model the ligaments as solid elements; this is common in models of other body regions (Freutel et al. 2014; Galbusera et al. 2014).

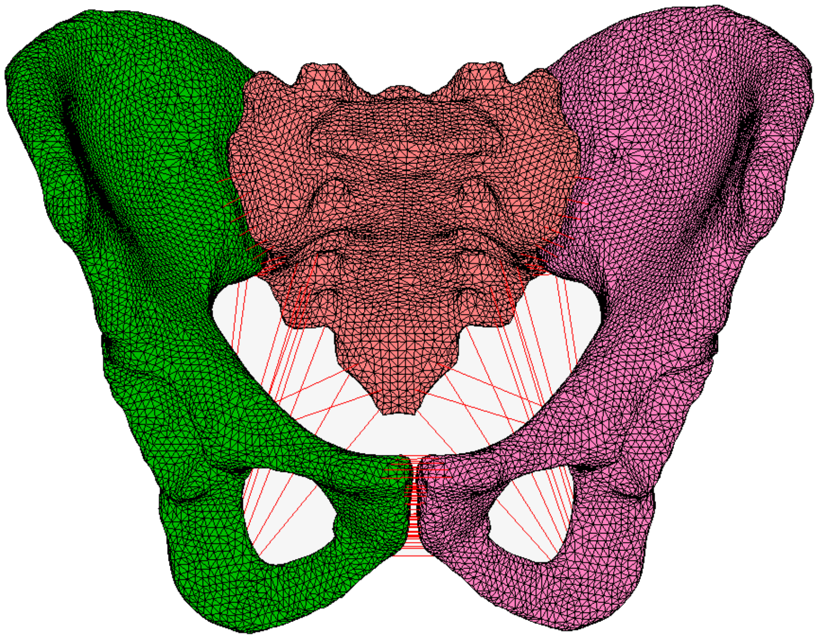


Figure 8.7: Pelvis mesh with associated ligaments (depicted by red lines).

8.4.2 Material Properties

The cortical and cancellous bones were modelled as homogenous isotropic materials with a Young's modulus of 17 GPa and 150 MPa respectively and a Poisson's ratio of 0.3 (Phillips et al. 2006; Cilingir et al. 2007; Clarke et al. 2013). The sacroiliac joint was included as ligamentous joints. Ligaments were represented using linear spring elements with tension-only stiffness (Zheng et al. 1997). The pubic disc was represented using spring elements with significant stiffness in compression and low stiffness in tension (Dakin et al. 2001). A set of stiffness values for each individual pelvic ligament was estimated from those used in previous studies (Zheng et al. 1997; Phillips et al. 2006; Clarke et al. 2013; Shi et al. 2014). The adopted ligament stiffness values are listed in Table 8.5.

Ligament	Stiffness (N/mm)
Arcuate pubic	500
Superior pubic	500
Anterior sacroiliac	2400
Short posterior sacroiliac	2400
Long posterior sacroiliac	530
Sacrotuberous	1200
Sacrospinous	800
Pubic symphysis	1500

Table 8.5: Structural properties of the ligaments of the pelvis.

8.4.3 Boundary and Loading Conditions

In order to replicate the cadaveric experiments, forces were applied at the acetabulum to represent load transfer through the femur at the ilium, which was free to move in any direction after impact. The base of the sacrum and the contralateral ilium were fixed in all degrees of freedom to represent the fixation in the physical experiment presented in Chapter 7 (Figure 8.8). Two sets of loading conditions were applied and run; one aiming to replicate the physical experiments, and one exploratory, whereby multiple directions of loading were applied to simulate a number of possibilities of limb flail. These are described in detail in the following 2 sections.

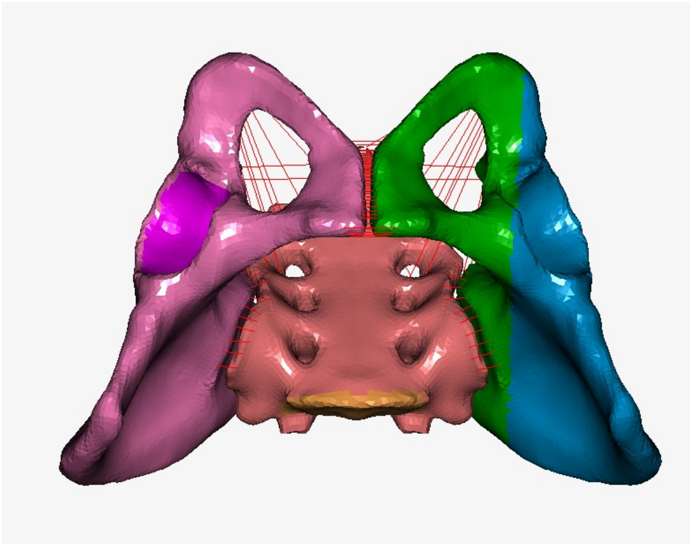
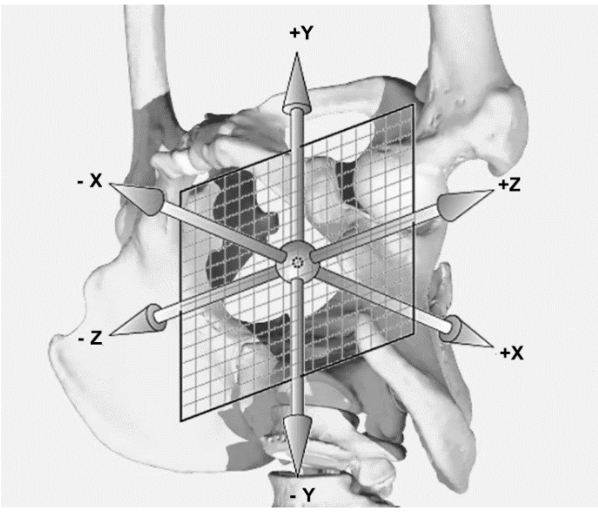


Figure 8.8: Pelvis mesh with ligaments (red lines). Sacrum and right hemipelvis were fixed in space to mimic the physical experiments in Chapter 7. Forces were applied to the acetabular wall (dark pink).

The loads were applied at the acetabulum in compression (-y) (or axial or superior force), anterior (-x), posterior (+x) and lateral (-z directions) as below (Figure 8.9).



Equivalent displacements	
+x	Posterior
-x	Anterior
+y	
-y	Superior
-z	Lateral
+z	

Figure 8.9: Pelvic disruption planes and equivalent pelvic movement directions for the bony and ligamentous FEA. +x=posterior, -x=anterior, -y=superior, -z=lateral.

8.4.4 Simulations Replicating the Physical Testing in Chapter 7

The following table presents three scenarios, aimed at replicating the physical experiments performed in Chapter 7. The applied magnitude and direction of forces and the resulting displacement and compression and tension data will subsequently be presented for each scenario (Table 8.6).

Simulation	Intact Pelvis	PS Divided	Anterior SI Divided
1	X		
2		X	
3		X	X

Table 8.6: Simulations 1-3 conditions under axial loading with anatomical variables within the pelvis.

Simulation 1: Acetabular Axial Load in the Intact Pelvis

This first simulation represents Tests 1 and 2 of the physical testing in Chapter 7, whereby axial loading was delivered via the femur, subsequently transferring the load to the acetabulum and into the hemipelvis. The applied forces and resulting displacement are presented in Table 8.7, and resulting tension and compression stress distributions throughout the pelvis are presented in Figure 8.10.

	x	y	z
Applied Force (kN)	0	-14	0
Resulting Displacement (mm)	12.1	-14	8.4

Table 8.7: Simulation 1: Applied directional forces and resulting displacement, axial load with intact pelvis. (-x=anterior motion, +x=posterior motion. –y=compression of femur -z=lateral opening).

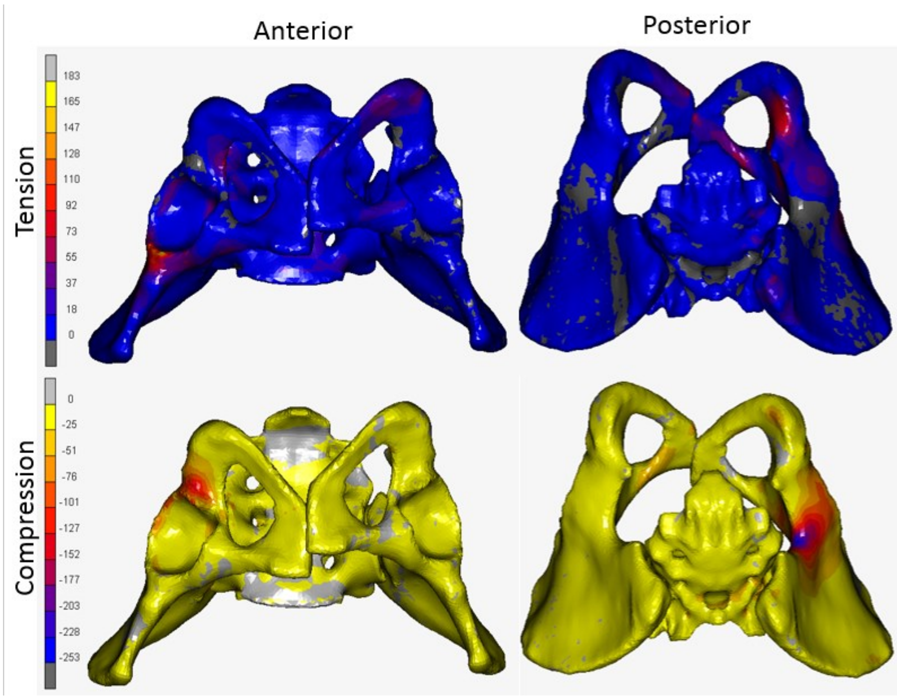


Figure 8.10: Simulation 1: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at axial loading through the acetabulum in an intact pelvis.

This simulation of axial load in the intact pelvis demonstrates a tension over the superior acetabulum, in which the load is distributed somewhat to the ipsilateral superior and inferior rami when viewed posteriorly. Corresponding forces are seen in the inferior acetabulum, which are at the posterior acetabular wall and the iliac wing on that side. There are very minimal forces, if any, in either tension or compression, acting on the PS or SIJs in pure axial loading of this intact pelvis. This suggests that in this loading condition, joint integrity is unlikely to get compromised in either the PS or the SIJ. This simulation leads to a greater disruption in the x plane (representing lateral disruption) than the z (representing A-P disruption) when looking at potential physical movement of the pelvic bones. In the physical experiments in this loading scenario, a fracture of the femoral neck occurred in one of two tests, with no pelvic injury in either. This suggests that the femoral neck is likely to be the weaker point than the pelvis in this loading mechanism, and this FE simulation supports this outcome.

Simulation 2: Acetabular Axial Load - Pubic Symphysis Divided

This simulation replicates Test 3 in Chapter 7 whereby axial load was applied to the pelvis with a divided PS to assess the contribution of this joint in resisting axial loading. The applied forces and resulting displacements are presented in Table 8.8, and resulting tension and compression stresses throughout the pelvis are presented in Figure 8.11.

	x	y	z
Applied Force (kN)	0	-14	0
Resulting Displacement (mm)	13.1	-15.6	8.3

Table 8.8: Simulation 2: Applied directional forces and resulting displacement with axial loading through the acetabulum with pubic symphysis divided. (+x=anterior motion, -x=posterior motion. –y=compression of femur +y=tension at femur. -z=lateral opening).

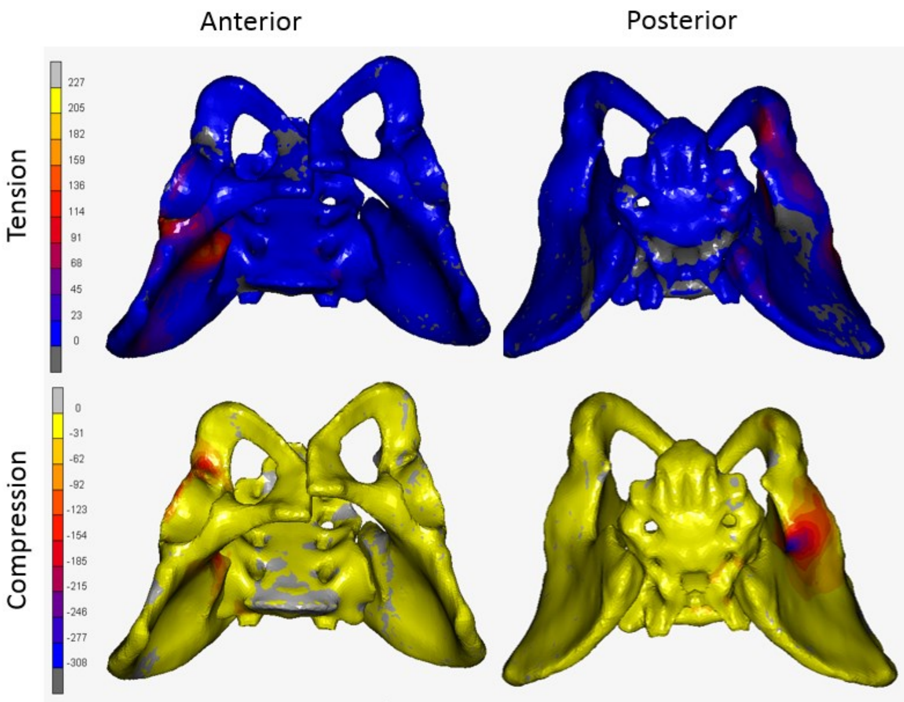


Figure 8.11: Simulation 2: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at axial loading through the acetabulum (pubic symphysis divided).

This simulation provides very similar results to the previous one, in which tension is observed at the superior acetabulum, and compression at the inferior acetabular wall, transferring to the posterior pelvic wing on that side. There is a slight area of potential compression at the SIJ on that loaded side anteriorly, but posteriorly, there is no tension nor compression noted. This suggests that the load pathway between the intact pelvis and the one whereby the PS is divided is similar. This reflects the experimental findings, in which the posterior pelvis remained intact in both test set-ups, the PS and SIJ retained their integrity, and the fracture of the femoral neck was more likely than pelvic disruption.

Simulation 3: Axial Load, Pubic Symphysis and Anterior SI Ligament Divided

This simulation replicates the physical experiments in Test 4 and 5 in Chapter 7 (Section 7.7) whereby the PS and anterior sacroiliac ligaments were divided. This simulation will be able to assess the relative contribution of both the PS and anterior sacroiliac ligament in resisting axial loading, when compared to the previous simulation in which the pelvis was intact. The applied forces and resulting displacement are presented in Table 8.9 and resulting tension and compression stresses throughout the pelvis are presented in Figure 8.12.

	x	y	z
Applied Force (kN)	0	-14	0
Resulting Displacement (mm)	13.5	-34.3	23.7

Table 8.9: Simulation 3: Applied directional forces and resulting displacement (axial loading through the acetabulum with pubic symphysis and anterior sacroiliac ligament divided). (+x=anterior motion, -x=posterior motion. –y=compression of femur +y=tension at femur. -z=lateral opening).

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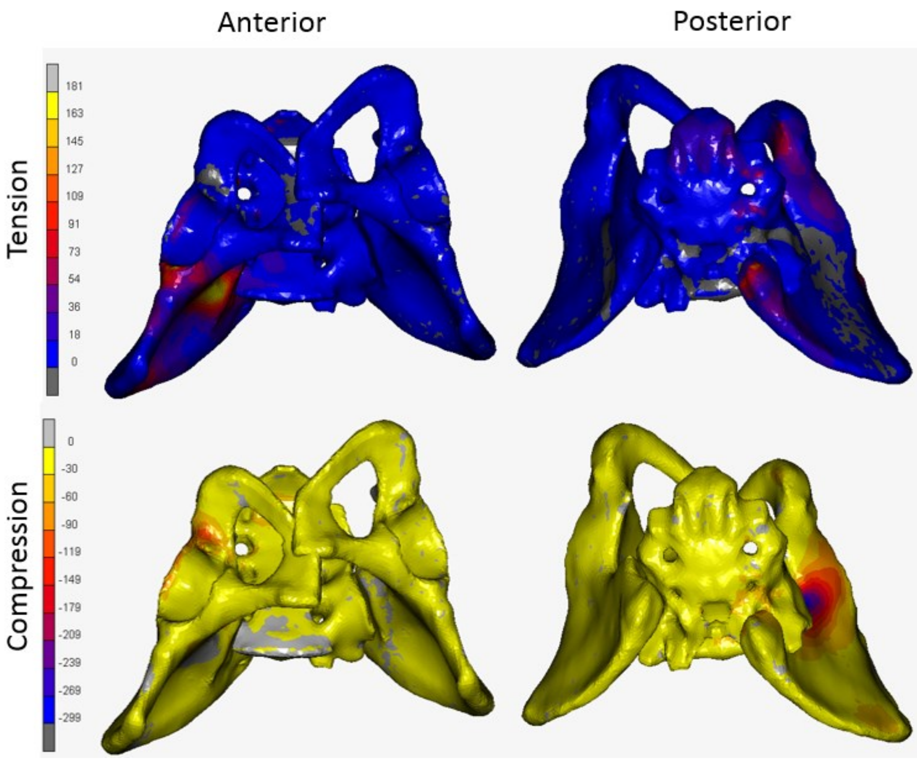

Figure 8.12: Simulation 3: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at axial loading through the acetabulum (pubic symphysis and anterior sacroiliac ligaments divided).

This simulation again presents a very similar load path to the two previous simulations, however, there is more posterior joint tension in the SIJ of the loaded side. Disruption distances noted are much greater than in the two previous simulations, demonstrating the higher vulnerability to disruption when ligamentous support to the pelvic is reduced, when compromised. This supports the shearing forces which occurred in the physical experiment at the joint of the same side subjected to axial loading.

Replication of Physical Testing: Summary

These replications of the cadaveric testing in Chapter 7 provide useful information on how the load is being transferred through the bony pelvis in similar conditions set by the experiments. They demonstrate that pure axial load as applied in the physical testing and these simulations, does not produce a very significant localised tension or compression at the SIJs, however, an intact PS demonstrates tension over both the superior rami, suggesting that the PS resists a lateral opening during application of axial load. It may be that axial loading leaves the PS susceptible to separation. This does not necessary lead to shearing at the SIJs. The combination of experimental and computational analysis of the effect of axial loading on pelvic injury suggests that additional loading mechanisms must be taking place in dismounted blast that result in SIJs shear.

8.4.5 Simulations Representing Additional Loading Patterns

The lower extremity can encounter many different loading patterns depending on the nature of the device itself and the location of the casualty relative to the device, in addition to variations in posture and gait at the time of injury. It has also been postulated that flail of the lower extremity may be a causative factor in pelvic joint separation, and if the PS opens in axial loading, that flail may be contributing to subsequent shearing at the SIJs. This is highly challenging to model physically in the laboratory. The measurement data presented in Chapter 6 demonstrated that the pelvis does move in both A-P, S-I and lateral planes in blast injury, however it is not yet known which loading directions lead to which disruption types, and therefore which loading patterns lead to PI where vascular injury is likely. The aim of the following simulations is to apply a variety of different potential loading scenarios that could be encountered in dismounted blast, in order to understand forces which, in addition to axial loading, may be occurring to produce the injury patterns seen in the blast pelvis. Specifically, the intention is to recreate potential shear mechanisms, which may cause lateral (abduction) loading at the acetabulum, anterior and posterior loading. These further combinations in addition to compression, simulating an element of axial loading in addition to these other forces, which may be the causative loading in lower limb and therefore pelvic flail. Once these loading patterns leading to PI with vessel disruption are known, mitigation can be developed to counter these forces. A further 10 loading conditions were simulated

(Table 8.10). These simulations 4-13 applied forces and resulting displacements are presented in Table 8.11.

Simulation	Lateral	Compression	Anterior	Posterior
4	X			
5	X	X		
6	X	X	X	
7	X	X		X
8			X	
9	X		X	
10		X	X	
11				X
12	X			X
13		X		X

Table 8.10: Additional loading scenario combinations

		x	y	z
Simulation 4	Applied Force (kN)	0	0	-14
	Resulting Displacement (mm)	0.3	4	-7.5
Simulation 5	Applied Force (kN)	0	-10	10
	Resulting Displacement (mm)	11.1	-13.6	21.4
Simulation 6	Applied Force (kN)	-8	-8	-8
	Resulting Displacement (mm)	1.5	-9.2	-3.6
Simulation 7	Applied Force (kN)	8	-8	-8
	Resulting Displacement (mm)	9.3	3.3	-5.7
Simulation 8	Applied Force (kN)	-14	0	0
	Resulting Displacement (mm)	-5.9	-14.1	6.4
Simulation 9	Applied Force (kN)	-10	0	-10
	Resulting Displacement (mm)	-4.8	-3.4	-4.4
Simulation 10	Applied Force (kN)	-10	-10	0
	Resulting Displacement (mm)	-5.9	-19.2	10.9
Simulation 11	Applied Force (kN)	14	0	0
	Resulting Displacement (mm)	7	14.5	-0.2
Simulation 12	Applied Force (kN)	10	0	-10
	Resulting Displacement (mm)	6.1	10.3	-6.2
Simulation 13	Applied Force (kN)	10	-10	0
	Resulting Displacement (mm)	15.3	-2.7	4.1

Table 8.11: Applied directional forces and resulting pelvic displacement in simulations 4-13 (+x=anterior motion, -x=posterior motion. –y=compression of femur +y=tension at femur. -z=lateral opening).

Simulation 4: Lateral opening

Lateral loading, with an intact pelvis, leads to a compression force acting on the iliac side of the sacroiliac joint, with no corresponding tension in that region. There is significant tension at the superior pubic rami, which may suggest the resistance to separation across the PS. The disruption distances are not particularly significant in any plane of disruption in this model (Figure 8.13).

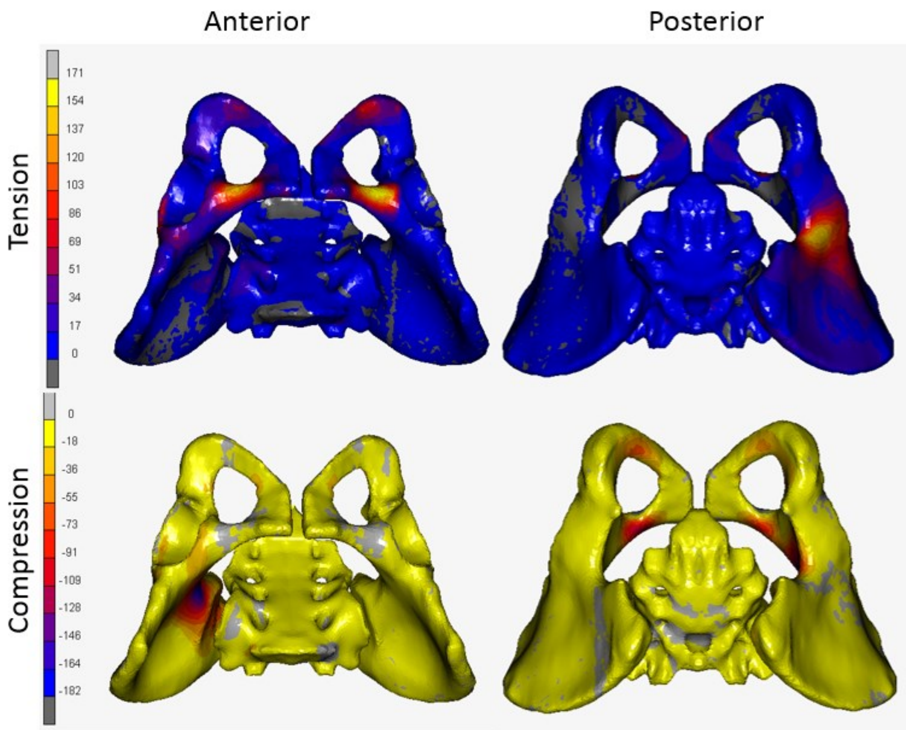

Figure 8.13: Simulation 4: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at lateral loading through the acetabulum).

Simulation 5: Lateral and Compression Forces

This simulation produces tension focused on the superior rami bilaterally, and superior acetabulum of the loaded side, as well as compression at the SIJ at the loaded side. This lateral and compressional movement may lead to opening of the PS due to the tensions seen on either side of the joint (Figure 8.14). Compression and lateral movement could be a loading pattern realistic of pelvic flail, and it appears this loading pattern may lead to PS disruption and realistic PI patterns, similar to those seen in blast.

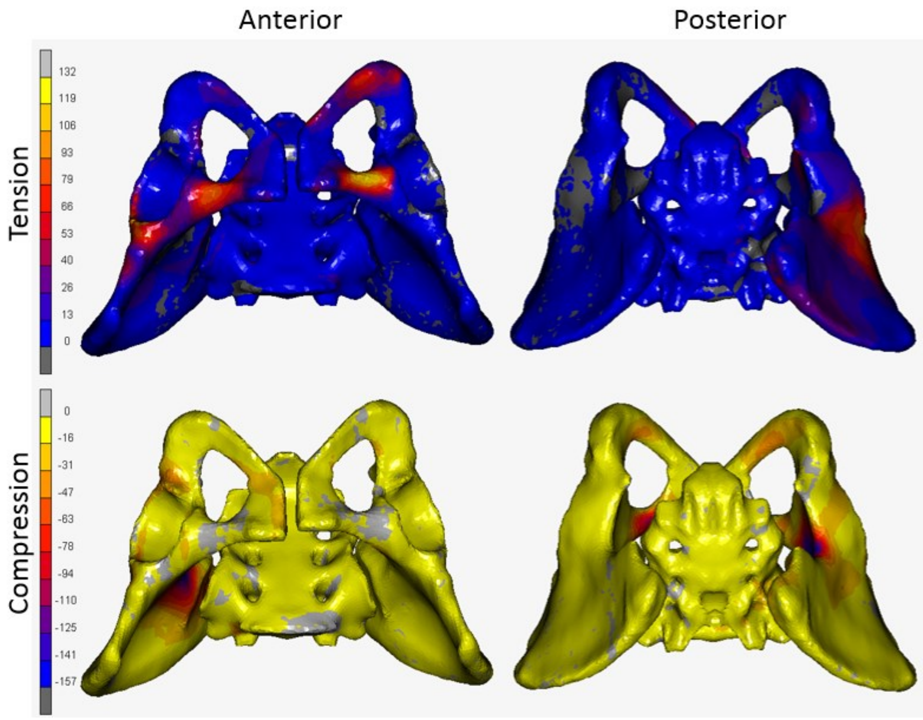

Figure 8.14: Simulation 5: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at lateral and axial loading through the acetabulum.

Simulation 6: Lateral, Axial and Anterior Loading

This simulation causes a strong tension across the superior rami of the loaded side, and across the iliac portion of the SIJ. Compression is noted at the contralateral rami, which may represent an attempted resistance to PS opening. This picture of deformation could represent the loading pattern realistic of a shear mechanism, which would lead to the opening of the SIJs and PS (Figure 8.15).

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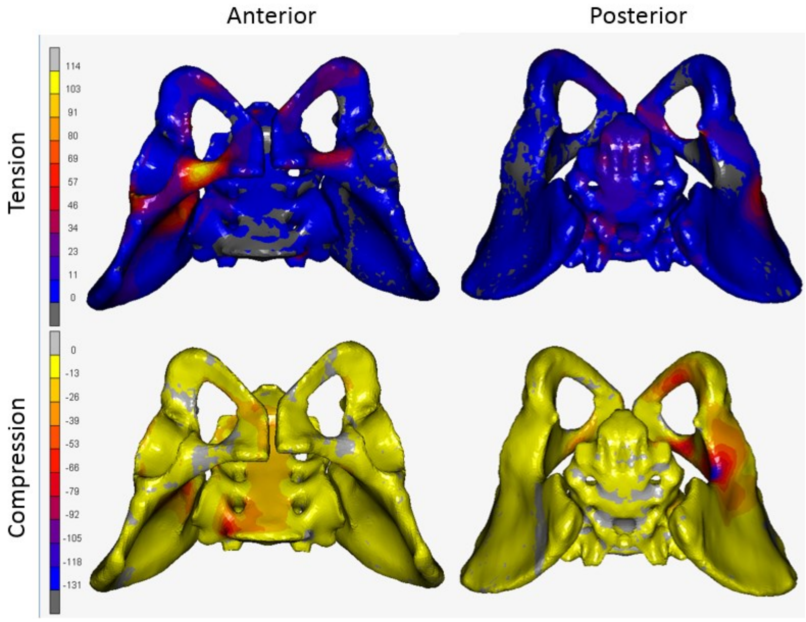

Figure 8.15: Simulation 6: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at lateral, axial and anterior loading through the acetabulum.

Simulation 7: Lateral, Axial and Posterior Loading

Anterior, lateral and posterior loading, interestingly, produces a very different loading pattern to lateral axial and anterior loading at the front, with the tension concentrated at the non-loaded side of the rami, and with no visible tension at the iliac portion of the SIJ. Instead, the iliac portion of the SIJ appears to be in compression, which is not likely to lead to separation at the joint, and more likely lead to a fracture (Figure 8.16).

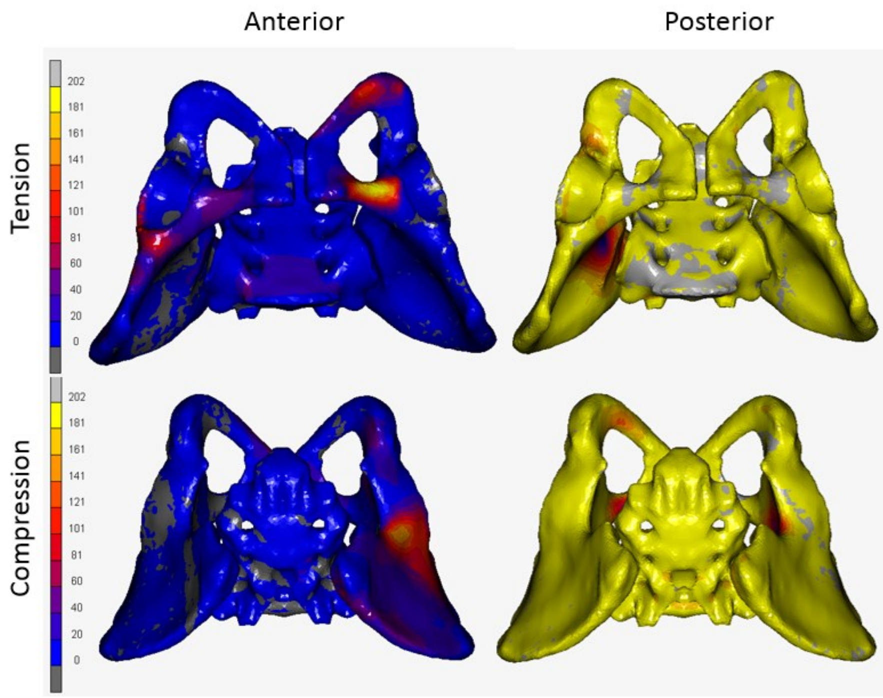

Figure 8.16: Simulation 7: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at lateral, axial and posterior loading through the acetabulum.

Simulation 8: Anterior Loading

Pure anterior loading causes a compression at the anterior acetabular wall as expected, but also produces a compression at the posterior acetabular wall, perhaps demonstrating the ability of the ball-and socket system to distribute loading to the entire acetabulum. There is relative sparing of both the SIJ and PS joints in this scenario suggesting that pure anterior load at the acetabulum does not shear the pelvis (Figure 8.17).

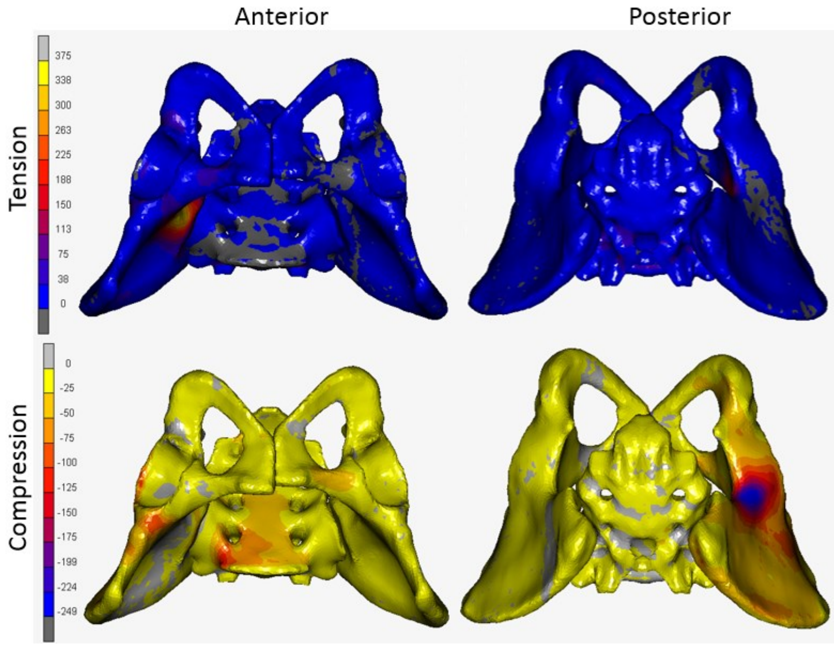

Figure 8.17: Simulation 8: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at anterior loading through the acetabulum.

Simulation 9: Anterior and Lateral Loading

This loading demonstrates very similar deformation as the previous scenario, suggesting that the contribution of lateral to anterior loading does not significantly change pelvic deformations (Figure 8.18).

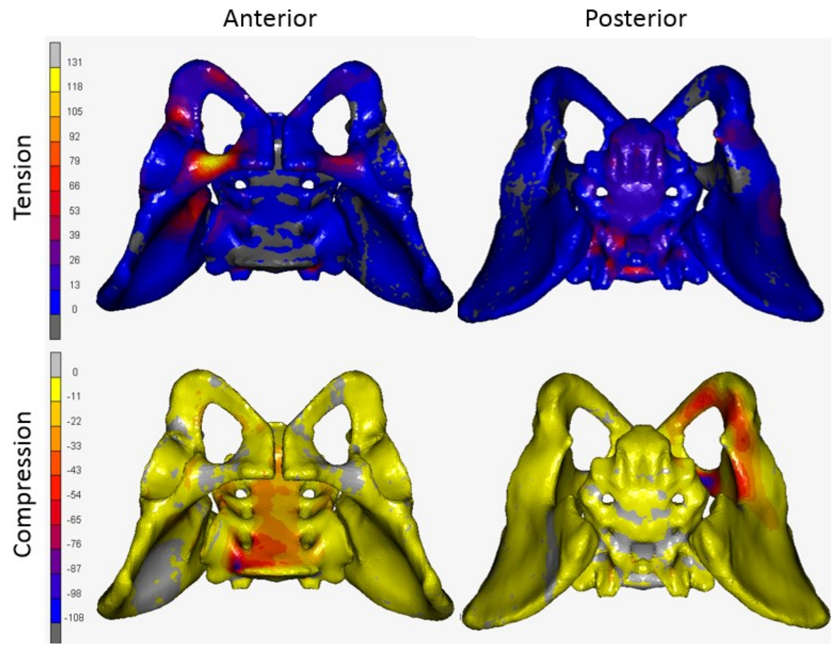

Figure 8.18: Simulation 9: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at anterior and lateral loading through the acetabulum.

Simulation 10: Anterior and Compression Loading

Anterior and compression loading causes a concentration of stress at the posterior acetabulum, with sparing of both the SI and PS joints, suggesting they are not at risk in this loading scenario. Therefore, an element of lateral loading is likely to be required to cause a lateral separation of the hemipelvis (Figure 8.19).

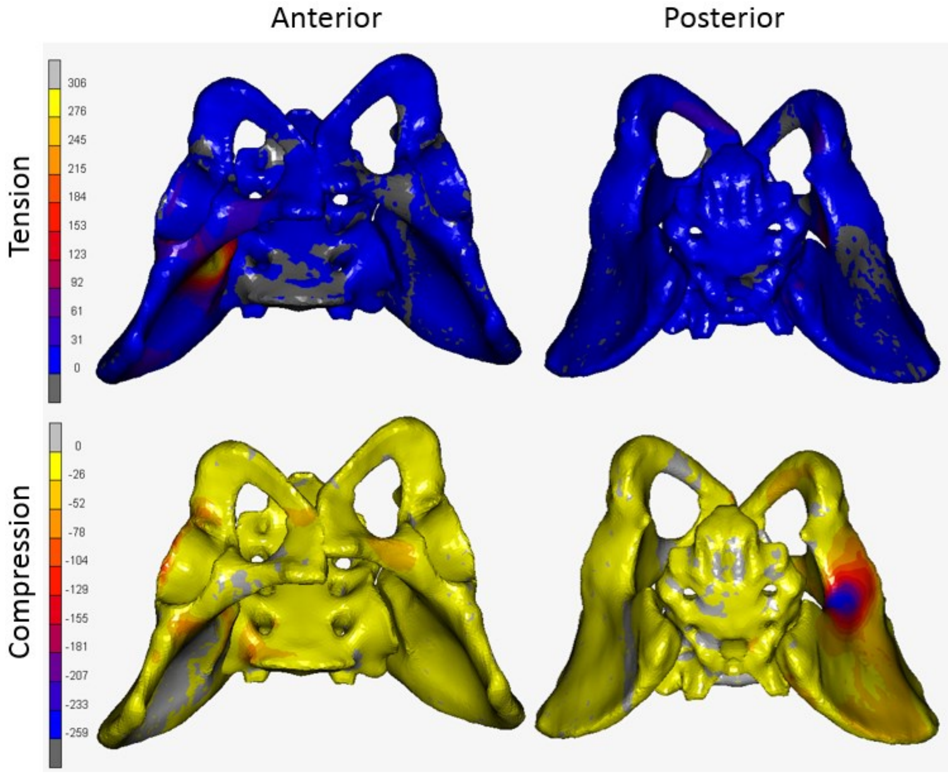

Figure 8.19: Simulation 10: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at anterior and compression loading through the acetabulum.

Simulation 11: Posterior Loading

Posterior loading in isolation leads to anterior tension and posterior compression, with sparing of deformation through the joints. This suggests pure posterior loading is unlikely to lead to severe life threatening pelvic fractures. This may also be an unrealistic loading condition, as an un-weighted posterior position is unlikely to be a trigger for an underfoot device, although if not victim operated, this loading condition could occur (Figure 8.20).

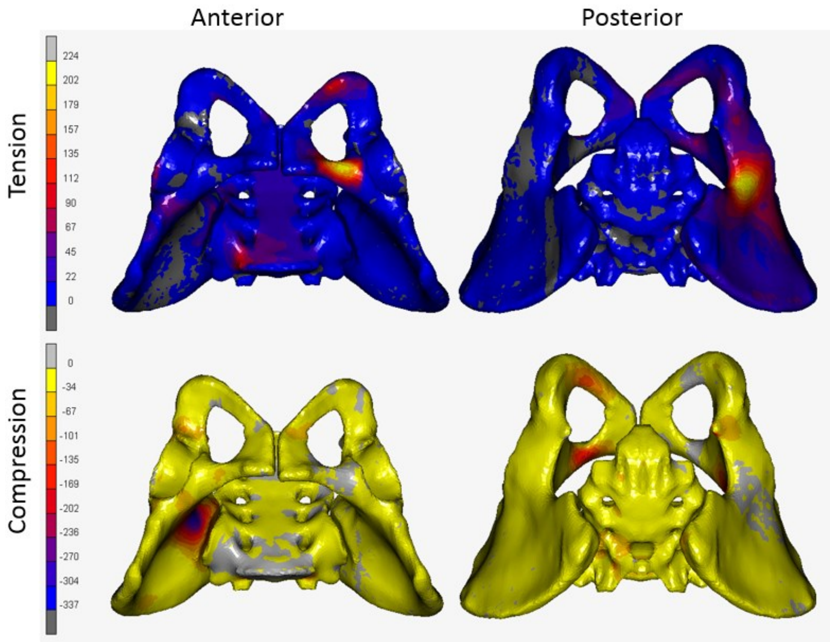

Figure 8.20: Simulation 11: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at posterior loading through the acetabulum.

Simulation 12: Posterior and Lateral

Posterior and lateral loading (without axial load) may occur in an un-weighted femur if weight is distributed on the contralateral side while in motion on foot (Figure 8.21). This simulation causes a contralateral superior rami, and posterior acetabular wall tension. There is some compression force to the iliac portion of the iliac portion of the SIJ, but this is more likely to lead to fracture rather than separation. This combination of stresses and strains is unlikely to lead to either anterior disruption at the PS nor SIJ rupture.

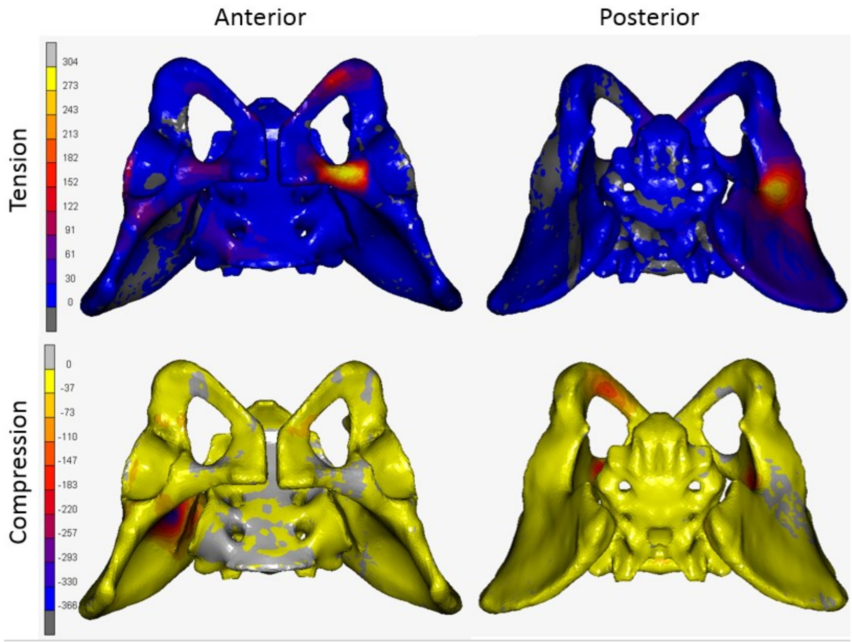

Figure 8.21: Simulation 13: A representation of the distribution of tension and compression forces throughout the pelvis in anterior and posterior views, at posterior and lateral loading through the acetabulum.

Simulation 13: Posterior and Compression

This loading scenario causes superior acetabular tension, and inferior acetabular compression. The tension forces are transmitted somewhat globally to the posterior iliac wing on the loaded side. There is additional tension at the sacrum, not seen in previous loading conditions, informing how sacral injuries may occur in particular situations in dismounted casualties (Figure 8.22).

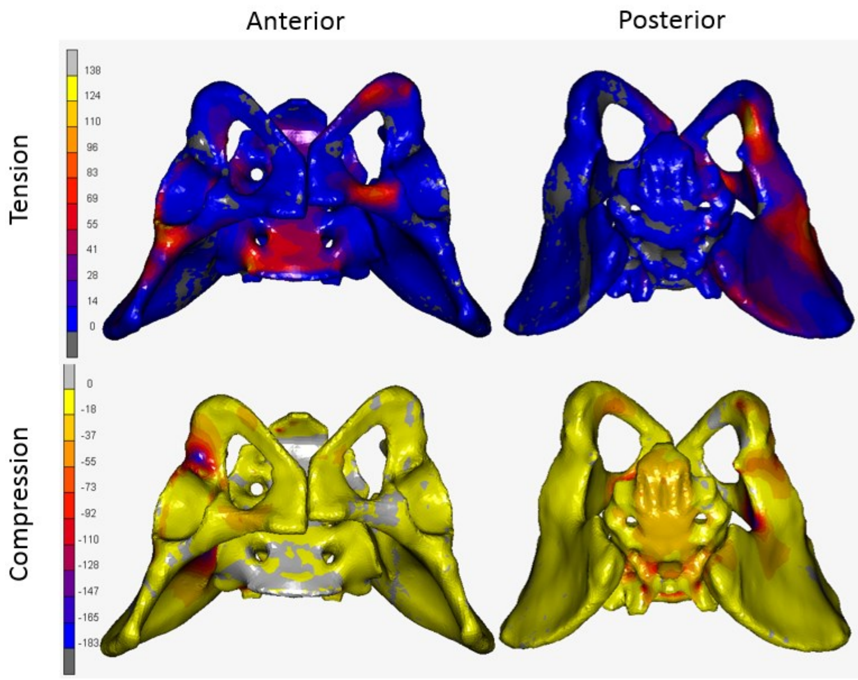

Figure 8.22: Simulation 13: A representation of the distribution of tension and compression stresses (in MPa) throughout the pelvis in anterior and posterior views, at posterior and lateral loading through the acetabulum.

8.5 Discussion

These simulations have been important to further test hypotheses made in the previous chapters, and to add further detail in order to confirm or refute mechanical hypotheses. The FEA of the vasculature has allowed vulnerable areas of the arterial tree to be identified using this mathematical model and to isolate areas of maximal stress and strain of the vessels; these areas are at the artery bifurcations at the common iliac, internal iliac, and the external iliac as it crosses the pelvic ring.

The later simulations replicating the experiments performed in Chapter 7 provide more detailed information than the physical experiments with regards to the stress distribution caused by the loading conditions that might occur in dismounted blast. They confirm that pure axial loading does not transfer concentrated loading to the PS and SIJs until the front of the pelvis and the anterior sacroiliac ligaments have failed. It is therefore highly likely that additional forces are implicated. Further simulation combinations allowed additional scenarios to be tested, and accepting the limitations of the model, it is likely that a combination of axial loading, lateral and anterior-posterior loading is required to see the disruptions noted in blast casualties.

FEA has inherent limitations which must be acknowledged; the higher the detail of an FE model, the more time consuming the development, run time and analysis. For the purposes of this thesis a number of assumptions and simplifications were made, in an attempt to allow for appropriate comparisons between loading scenarios to be made and therefore aid in answering the research questions of this work.

The FEA representing the pelvis and vasculature focusses on the major arterial tree, and does not discuss venous disruption or smaller arterial branches. This was a decision taken to focus on the most common vascular injuries found in the data analysis in Chapter 5; these injuries are also the most fatal, as they involve the higher pressure and greatest diameter vessels (Kelly et al. 2008). Arterial structures are less likely to resolve spontaneously if ruptured, and less likely to respond to conservative measures such as pelvic binding and blood volume replacement in isolation (Miller et al. 2003). The high morbidity of these larger vessel injuries, and difficulty in controlling them in the pre-hospital environment, justifies their focus in this study, which aims to understand injury mechanisms for the purpose of developing mitigation. However, the addition of smaller blood vessels and the venous system would be a highly useful addition to this model. In addition, the vessels were modelled as solid structures with material properties taken from arterial wall structures, and not as fluid filled structures. This means that there may be differences in the properties of the FEA vessels and vessels in vivo. The vessel attachments are also approximated, as the vasculature is tethered at multiple points such as branches and surrounding connective tissue. These connections are difficult to assess accurately. Despite these limitations, this is the first FEA to represent the pelvic vasculature in situ within the bony pelvis, and therefore provides a very important initial starting point for future model development, and the understanding of vessel behaviour in pelvic fracture.

The second FE model, comprising more detail of the bony and ligamentous structures, reproduced the loading environment of the experiments, and additional loading environments associated with the disruption of the pelvis in dismounted blast. Again, this model is the first to simulate this environment, and discuss transfer of load throughout the pelvis in response to an applied load. The material properties of bony and ligamentous structures, as in the vascular model with regards so the vessels, are based on values in the literature. Therefore, stress and strain values are not necessarily representative of actual values, but can be used to compare one region to another within the pelvis and to assess the ratio of disruption in one region compared with another. Furthermore, the absence of additional soft tissues, for example, muscle, skin and intra-abdominal organs may have affected results, although the lack of data on their behaviour would induce further uncertainty. In addition, the increased number of elements and interactions modelled would mean highly increased run times, rendering their inclusion impractical and heuristic. The static nature of these tests was also necessary to keep run times practical, which for the very first FEA of this nature, is an acceptable starting point on which to base the development of further models. A dynamic model would have produced data on deformations with time, and could be useful in further work on analysing in more detail the effect of loading characteristics on PI patterns.

8.6 Conclusion

This FEA suggests that artery bifurcations, and the crossing of the pelvic brim are important locations where vascular injury is likely, which is useful for clinical management of these cases. There is a significant difference between 10 and 20 mm of disruption of the pelvis in all planes, and therefore restricting movement of the pelvis to

10 mm of opening in all planes using PPE may be a realistic starting point for developing PPE that is focussed on preventing arterial disruption at the pelvis.

The second FEA focussing on bony and ligamentous structures confirms that axial loading alone is unlikely to cause the significant disruptions at the PS and SIJs seen in the blast pelvis. The addition of compression and lateral forces created deformation pictures similar to those expected in blast pelvic loading, which is likely to be representative of flail of the lower extremity.

The prevention of disruption in both SI-PS and lateral movement is therefore important, but as confirmed in Chapter 6, it is possible that purely the prevention of lateral movement may be preventative of movement in all other planes. Further testing, both computational and physical would enable this question to be answered, and recommendations for alterations to PPE to be made. The FE models developed here could be used as a basis for developing and testing PPE design concepts before prototyping them.

The final chapter will summarise the information from the clinical data, measurement data and statistics, cadaveric testing, and the FEA to conclude the findings of this research, and suggest clinical applications and further work

CHAPTER 9

SUMMARY, FUTURE WORK AND CONCLUSIONS

The research presented in this thesis has aimed to produce an analysis of lower extremity injury secondary to an explosive insult, and present the cause of fatality in this patient group. It has subsequently focussed on PI, as the injury that contributes the most to fatality in the lower extremity. This work has helped to further understand lower extremity and pelvic blast injury, which is important to help develop methods to reduce fatality due to injury of this body region in explosive events. This chapter summarises and discusses the research presented in this thesis and makes recommendations for the application of the new understanding this study has enabled. It also addressed limitations, and suggests plans for further work based on the findings of this project.

9.1 Summary

Despite the closure of the active conflicts in Afghanistan, blast events in conflict are likely to continue for the foreseeable future. Therefore the drive to further understand these injury mechanisms is important, and maintaining the momentum of research in this area is vitally important. This thesis has confirmed the extent of lower extremity blast injury, and that pelvic fracture in lower extremity injury increases the chance of fatality, and that fatal PIs occur mainly in dismounted casualties. This is often in association with traumatic amputation, which is mostly related to high amputations, but can occur at any level in association with the pelvic injury. SIJ and PS opening is the most common injury pattern in dismounted blast casualties, and posterior vascular injury, and primarily arterial injury, has been isolated as the main cause of fatality. A quantitative measure to assess the extent of pelvic disruption and statistical analysis lead to all planes of disruption being associated with the presence of vascular injury, and with lateral separation being the most likely predictor of pelvic vascular injury. The FEA simulating the arteries within the pelvis, and likely disruption patterns seen in blast, lead to the identification of particular locations within the arterial network that are vulnerable to rupture in bony disruption of the pelvis. These are at the bifurcations of the common and internal iliac, and as the external iliac artery crosses the pelvic inlet. The calibre and flow within these vessels are such that their rupture could lead to early pre-hospital exsanguination on operations, as these injuries are too proximal for the application of a tourniquet, with few other options for haemorrhage control except for operative intervention, which may not be immediately available.

The mechanism of this injury pattern is complex, and does not fit into the standard primary, secondary, tertiary categories of blast injury. Both blunt force leading to the transmission of axial load into the pelvis, flail of the lower extremity, and secondary blast fragmentation injuries are all mechanisms that have been developed from injury pattern analysis and knowledge of the behaviour of explosions, and their resulting effects on the body. From these three injury theories, a testing method was developed and an experimental platform created, to simulate solid blast leading to axial load in the pelvis. The results of this were a preferential breaking of the femoral neck, with no pelvic injuries at the axial loads applied. Pelvic shear did occur in a similar way to that seen in blast PIs, but only in compromise of the anterior pelvic ring. FEA recreating these experimental conditions also suggested that axial loading alone did not produce stresses and strains likely to lead to SI and PS disruption. This suggests that loading pathways in addition to axial loading must be implicated to cause these injuries. Further FEA was performed in additional loading scenarios, which produced deformations likely to cause SIJ and PS rupture in a combination of axial, lateral and either anterior or posterior loading. These findings suggest that in addition to axial load, lateral and A-P directions of movement are required to separate the pelvic joints, which implicates flail of the lower extremity causing a subsequent flail at the pelvic joints, as the injury mechanism occurring in the blast pelvis

The following section will discuss potential limitations of this work, how these will be addressed, and the impact and further applications of this research.

9.2 Limitations and Future Work

With regards to the data analysis section, the casualties that died from an additional injury remote to the pelvis were removed in this study, as fatality due to PI was the research focus. However, now that the cause of fatality has been ascertained, these casualties could be reviewed, to increase the size of the database, purely for the purpose of reviewing pelvic injury patterns caused by particular loading scenarios. In terms of additional ways to expand the dataset, it is unlikely that such a large cohort of blast pelvic injuries will be available in the future, and therefore this is likely to be the most robust blast pelvic dataset available in the foreseeable future. Compared to other nations involved in the conflicts in Iraq and Afghanistan, even though they have data collection systems, it is considered that the JTTR offers the most complete dataset currently available with regards to military trauma. To further expand the knowledge with a slightly different patient group, comparisons of this work could be made with severe pelvic fracture in civilian cohorts. This work has created valuable testing strategies for assessing the mechanism of pelvic injury, and therefore, these valuable resources could be used to assess pelvic fracture mechanisms in other incidences of pelvic injury, for example, in falls from height, motor vehicle incidents, or high impact sporting injuries.

Due to limitations associated with cadaveric testing, only one injury path, axial load, was tested physically in the laboratory. Further lab based experiments, when further cadavers become available, could include testing different postures of the femur, similar to those additional simulations performed in Chapter 8, with lateral, anterior and posterior loading scenarios, as well as axial loading in differing combinations. This will validate the outcomes of the FEA, and test these theories in practice to obtain injury data. Dual loading of both femurs could also be performed, to assess injury patterns when load is transferred through both lower limbs. These additional tests will complete the review of the solid blast theories for the blast pelvis. With regards to secondary blast loading theories, an experimental plan will need to be created to test the destructive potential of fine particles encountered in blast injury, to replicate the ‘sand blast’ effect on tissues, which is often noted anecdotally, although not yet fully understood. This is important for including this injury mechanism (or excluding it) from the mechanistic theories of pelvic disruption in explosive events. Developing an understanding of this mechanism would lead to the development of protection that could address protecting against secondary fragmentation injuries in addition to mitigating the bony injury,. Developing this testing capability is vital to research in all soft tissue injuries in blast, and will have wide-reaching applications to many body regions.

The limitations of the FEA with vasculature included the modelling of the artery as a solid element due to the complexity of modelling it as a hollow structure with an internal pressure similar to that of the artery in situ. This is a further development of the model, and a method that could provide more accurate vessel deformation patterns. In addition, the material properties used were gained from aortic physical tests, due to the absence of iliac artery properties in the literature. These properties could be obtained from physical laboratory based testing, therefore this would be a consideration in further work. The bony and ligamentous FEA did not include soft tissues, which could be included in subsequent models. In addition, more specific material properties of the pelvic bone, PS and SIJs could be gained, which would provide more accurate deformation data to include actual values, rather than the relationship between different sections of the pelvic anatomy. Both the vascular and bony FE models could also be run as dynamic events, which would provide data on deformation at many different time points in the pelvic injury event, and perhaps provide a more detailed value on exact disruption levels likely to lead to both joint and subsequent vessel injuries. These models would be complex and have a longer run-time compared to those presented in this thesis, but may be a valuable addition to the overall clinical picture.

As a summation of the current knowledge gained from the detailed analysis in this work, it can be hypothesised that circumferential support to the pelvic bones to prevent lateral separation would have a preventative effect on all planes of movement of the pelvis, and help to prevent pelvic vascular injury. Additional protection over the external iliac to femoral artery junction at the pelvic brim may also be advantageous, as this is also an area of vulnerability in the arterial system. Following on from this research, it must be ensured that these findings have a tangible impact that will carry forward to practical applications in warfare. This research will therefore be communicated to the Lower Extremity Trauma Working Group, at Defence Equipment and Support, MOD Abbeywood. This sharing of findings in this work will enable the current PPE to be evaluated for efficacy and potential changes that may be necessary to take into account the findings from the research presented in this thesis.

9.3 Conclusions

This research provides an important analysis of the PIs of the recent conflict, and has enabled the creation of mechanistic theories developed as a result of this analysis. Physical and computational testing has begun, and recommendations can be made to the appropriate subject matter experts in lower extremity protection. Further work will continue as planned, and as required, as further research questions are encountered.

It is hoped that this greater understanding of lower extremity trauma and PI can enable PPE to be tailored to support these injury mechanisms, and fatality can be reduced in similar incidents where blast is the primary mechanism of wounding. This research goes some way to minimising the human burden of war, reducing fatalities and mitigating severe, debilitating injuries. This can enable soldiers and commanders to perform their activities confidently in the knowledge that their equipment has undergone the scrutiny of the clinical and academic community.

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PUBLICATIONS AND PRESENTATIONS

Journal articles

Webster, C., et al. "Fracture patterns in pelvic blast injury: A retrospective analysis and implications for future preventative strategies." *Bone & Joint Journal Orthopaedic Proceedings Supplement* 97.SUPP 8 (2015): 14-14.

Webster, C., et al. Traumatic Amputation in Blast Injury: Where is the focus for improving outcomes? Military Medicine. Accepted pending revisions.

Presentations

Webster C, The Blast Pelvis: Defence Equipment and Support (DE&S) presentation to 3* level on research activity at Imperial College London Blast Laboratory.

Webster C., The Blast Pelvis: Defence Equipment and Support (DE&S) presentation to 3* level on research activity at MOD Abbeywood. July 2017.

Webster C., Association of Trauma and Military Surgery. The Blast Pelvis. May 2016.

Webster C., Presentation to Secretary of State for Defence UK and US on research activity at Imperial College July 2016.

Webster C., Combined Services Orthopaedic Society Conference. Pelvic Fracture Patterns and Posture at the time of Injury. May 2016.

Webster C., Tri-Service Radiology Conference: Mapping the Blast Pelvis. June 2015.

Webster C., Combined Services Orthopaedic Society Conference. Fracture Patterns in Pelvic Blast Injury. May 2015.

Poster Presentations

Webster C., et al. Blast Pelvic Fracture and Genitourinary Injury. Presented MHSRS August 2015.

Webster C., et al. Fracture Patterns in Pelvic Blast Injury. Presented MHSRS August 2015.

Webster C., et al. Blast Pelvic Fracture: Where is the focus for improving survivability? Presented MHSRS August 2016.