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Analysis of Blunt Trauma Injuries: Vertical Deceleration Versus Horizontal Deceleration Injuries

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ABSTRACT: There are several similarities found in blunt trauma injuries to humans sustained as a result of vertical deceleration (falling) and those sustained as a result of deceleration in a horizontal plane (automobile accidents). However, examination of the patterns of traumatic skeletal injuries can distinguish those injuries associated with falling from heights from those associated with automobile accidents. While there is considerable variation within each type of blunt trauma injury dependent on the angle at which one falls or is struck, there are several characteristic skeletal features associated which each type of trauma. In this study we review both the current literature and human skeletal remains from the University of New Mexico's Documented Collection known to have been subjected to blunt trauma. This collection is used to characterize and differentiate the pattern of skeletal injuries to various parts of the body for each type of trauma. These assessments are applied to investigate the traumatic skeletal lesions observed in a forensic case where the manner of death is unknown. Analyses suggest two possible scenarios that would explain the death of the individual investigated, with death most likely related to a vehicular-pedestrian accident.

KEYWORDS: forensic sciences, forensic anthropology, blunt trauma, horizontal deceleration injuries, vertical deceleration injuries

The discovery of a partially decomposed human body in rural Illinois has resulted in questions concerning the manner of death of the individual. The remains of a 26-year-old, 5 ft-6 in.-tall male were found in a wooded area in the fall of 1994. This individual sustained extensive trauma at or around the time of death to the thoracic region, including right ribs 1, 2, and 9, and left ribs 1, 6–12. There were also fractures to the thoracic vertebrae (T4, T7-T12) and the first lumbar vertebra, as well as the right scapula and the left clavicle. Because of the location in which the individual was discovered, death as a result of falling from a tree, whether accidental or suicidal, has been hypothesized. However, the injuries sustained by this individual were extensive and consistent with injuries often sustained from vehicular-pedestrian accidents. While the remains were found in a wooded area, initially suggesting that death most likely occurred in this area, it is possible that the body was transported after death. The position of the body with respect to the injuries sustained is therefore of critical importance in assessing the manner of death. Therefore, our goal in this study is to examine the injuries with respect to both types of most likely trauma (falling from a height and struck by a vehicle) to ascertain the most probable manner of death.

Biomechanics of Blunt Trauma

There are numerous factors that affect the severity, extent, and appearance of injuries due to blunt trauma. Some of these factors include the amount of force delivered to the body, the time over which the force is delivered, the area struck, the extent of body surface over which the force is delivered, and the nature of impact (1). When an external force is applied to the body, the nature and extent of injury is produced by the interaction between the physical factors of the force and the biomechanical factors of the body (2). For instance, when a moving body strikes a stationary rigid surface, the extent of injury is associated with the ability of the stationary object to cease forward motion of that body. Therefore, the injury-producing potential of a body in motion is a ''function of the dissipation of kinetic energy and the tendency upon impact to displace the tissues in the direction of the motion, while the movement of the body itself is arrested'' (2).

Also, when the force of impact is distributed over a greater area, the force is dissipated, thereby resulting in less severe injury than would occur if the force was delivered over a smaller area (1,2). This is evidenced in the more severe injuries that result when deceleration forces are applied to the body in the vertical axis compared with the transverse axis (2). For example, a force delivered to a rounded region of the body, such as the top of the head, will produce a more severe injury than the same force delivered to a flat region of the body (i.e., back), where there is a greater area of contact and greater dispersion of force (1). Additionally, depending on the angle at which one falls, or the angle at which one gets struck, the nature of injuries sustained varies.

Biomechanics of Falls

Injuries evinced from falls are often due to direct impact or transmitted force of impact (3). However, injuries resulting from direct impact are commonly more severe, while injuries resulting from transmitted force are less severe, as the energy transferred by the counterforce is absorbed by the most external tissues (3). Because of the effects of direct impact, the parts of the body that hit the ground initially experience the greatest injury. ''At the moment of impact, a falling body undergoes deceleration and the amount of the kinetic energy transferred to the ground reacts with an equal amount against the body itself'' (3). Injuries result from the resorption of lost energy.

Factors that influence the magnitude of injury in vertical deceleration accidents include mass, acceleration, and deceleration of the body, as well as duration and area of application of the force (2). For example, in deceleration forces, ''the slower the application

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of the force, the greater the distance through which the body is decelerated, the slower the release of kinetic energy'' (2). Therefore, the extent of injury is less than would occur if the application of force was faster.

Biomechanics of Vehicular-Pedestrian Accidents

While the extent and nature of injuries resulting from deceleration in a horizontal plane (vehicular accidents) are influenced by several of the same factors that influence vertical deceleration injuries (i.e., mass, acceleration, deceleration of the body, and duration and area of application of the force), body displacement needs to be considered. For instance, if the body moves with the impact, the period of time over which the energy is delivered is increased. As a result, the severity of the injury decreases (1).

The Skeletal System

As already discussed, the extent, severity, and nature of blunt trauma injuries sustained from vertical deceleration and horizontal deceleration accidents are a result of varying factors. While the types of blunt trauma injury include abrasions, contusions, lacerations, and fractures of the skeletal system, only the last type of injury is of importance in this study.

Fractures of the skeletal system result from either direct or indirect application of force to a bone. Fractures occur when stress from the force increases, producing ''minute imperfections in the material'' (4). Depending upon the amount of force applied to the bone and the area to which the force is applied, the type of fracture (i.e., focal, crushing, penetrating) is determined (1,5). Also, the age of the individual is an important factor in whether the bone fractures at all. Because of the plasticity of bones in children, adolescents, and young adults, severe trauma to the chest may cause extensive compression to the flexible thoracic cage without fracturing the sternum, ribs, and/or costal cartilage. However, in adults the same crushing force will often fracture the sternum, ribs, and costal cartilage (1). Additionally, older individuals and individuals suffering from certain maladies, such as osteopenia, may be more susceptible to trauma.

There are several biomechanical factors that determine whether a bone will fracture, including the force applied and the mechanical properties of bone (6). When local stresses or strains exceed the ultimate strength of a bone, fractures occur (6). As mentioned earlier, the region of the body subjected to force influences the extent of injury. Therefore, a long bone that is subjected to axial loads is more resistant to fracture because the forces are distributed over a larger surface area which dissipates the force (6).

Vertical Deceleration Injuries

Vertical deceleration injuries are often associated with falling or jumping from heights. Acceleration of a falling body contributes to the severity and nature of injuries sustained, as discussed earlier. Acceleration in free fall is independent of mass and depends mainly upon the distance fallen (7). Other factors that influence acceleration include air drag of clothes (if the altitude is high enough), position of the body, and humidity (7). The velocity at body impact depends primarily upon the position of the body; it is faster in a vertical position and slower in a horizontal position (8). Height of the fall also influences severity of fractures, with a high correlation between presence and severity of fractures and height fallen (9).

Vertical deceleration injuries produce a distinct pattern of blunt trauma that is predictably different from injuries seen with other forms of blunt trauma (9). In particular, this distinct form of blunt trauma varies considerably from horizontal deceleration injuries attributed to vehicles (9). There are some regions of the body that are usually injured because of the ''natural orientation of the body along its center of gravity during the fall'' (3). However, the planes of orientation of the body are related to height. For example, with heights up to 40 ft (12 m), head injury usually results (3).

Lewis et al. (7) examined the extent and type of injuries sustained in 53 individuals who jumped from a height of greater than three stories onto concrete. The most common injury was to the skull ($n = 19/53$, 35.8%), followed by the spine ($n = 12/53$, 22.6%) and the face ($n = 9/53$, 17.0%). In a similar study, Scalea et al. (9) analyzed 161 falls from heights. Fractures were the most common injury sustained, with 79% of the individuals suffering from at least one major fracture (i.e., long bone, spine, pelvis). Thirty-eight (23.6%) individuals suffered spine fractures, most commonly at the thoracolumbar junction, with 74% of them sustaining a major compression or burst fracture (9, p. 708). The thoracolumbar junction is more susceptible to injury than other areas of the spine because of the decrease in rib restraint and the changes in disc size and shape that occur relatively acutely in the transitional area between the upper thoracic and midlumbar vertebrae (10). Other studies of injuries produced by falls also emphasize the prevalence of skull fractures and spine fractures (8,11).

As mentioned earlier, the angle of the body at impact also influences the nature of injuries sustained. Compression fractures often occur in the lower region of the spine as a result of primary feet or buttocks impact in vertical deceleration accidents (2,11). By contrast, angulation fractures of the spine often occur from primary side impact. Both compression and/or angulation fractures can also result from primary head impact (11). Angulation fractures of the spine are also associated with sternal fractures (11). Other common skeletal fractures associated with falls include the ribs, the pelvis, and the lower extremities (11,12).

Because the planes of orientation of the body are related to various heights, the injured regions are directly related to the height of the fall (3). For falls up to 40 ft (12 m), head injuries are most common. However, with the increase in height, the probability of chest and abdominal injuries increases, while head injuries decrease (3). Lower limb and pelvic fractures also increase with an increase in height, while forearm fractures are more common in low falls. Height of the fall also differentially affects the distribution of vertebral fractures. Fractures to the cervical vertebrae are more common in low falls, while fractures to the thoracic vertebrae are associated with severe vertical impact often resulting from higher falls (3). Therefore, while the probability of fractures to the skull, forearm, and cervical vertebrae is greater in low falls, the probability of fractures to the chest, pelvis, and thoracic spine is greater in higher falls.

Horizontal Deceleration Injuries

Injuries resulting from abrupt acceleration/deceleration in a horizontal plane are often associated with vehicular accidents. In this study, vehicular-pedestrian accidents are emphasized. Type and severity of injury are influenced primarily by the speed and the size of the automobile and the position of the body during impact.

Fractures of the lower extremities are common and most often a result of direct impact to that region. Trauma to the cervical spine, in particular the lower cervical spine, is also common in motor-vehicle-related injuries (13). Hyperextension of the spine can result from force resonating through the body after impact, thereby causing fracture-dislocation of the spine. A sudden acceleration applied to the lower body and inertia of the relatively large head can produce hyperextension of the spine (13). With severe extension, a symmetric break may occur across the lateral masses, pedicles, and laminae (13).

Blunt trauma to the chest is also common with motor vehicle accidents, which is manifested in rib fractures. Similar to a fall, during motor vehicle accidents sudden horizontal acceleration or deceleration forces are applied to the thorax (13).

Tonge et al. (14) examined 1004 traffic-crash fatalities, 306 of which were pedestrians. Among the pedestrians, skull fractures were most frequent, occurring in 59.3% of the sample. Spinal fractures/dislocations were also common, with 20.9% displaying cervical injuries and 9.1% displaying thoracic injuries. Fractures of the pelvis (37.9%) and lower extremities were also frequent (12.7 to 25.4%).

Mechanisms of Injury

Ribs

Rib fractures are most frequently associated with blunt chest trauma and are more common in the lower ribs (15). The upper ribs have a smaller radius of curvature due to their circular shape and they are protected by the overlying muscles and scapula (15). Therefore, fracture-producing forces are greater for the upper ribs compared to the lower ribs. Fractures of the upper ribs (R1-R3) are often associated with extreme force (1,15).

Multiple rib fractures are often associated with vehicle accidents. However, different modes of injuries will produce varying patterns of rib fractures. Severe anteroposterior compression of the chest, such as associated with a fall from a height, may result in fractures of the ribs most often on their curved lateral portions. If the force is from the dorsal aspect of the body, the ribs tend to fracture near the spine. If the force is from the sides of the chest, the ribs tend to fracture near the spine and the sternum (1). Therefore, by examining the pattern of rib fractures, the nature of the impact may be ascertained.

While rib fractures are a common type of injury associated with both vertical and horizontal deceleration injuries, fractures of the first-rib are not common and are considered a hallmark of extreme force (15). In fact, in a study of over 60 individuals who suffered chest trauma due to vehicular accidents, fractures of the first-rib were not seen ''unless massive force was applied to the upper torso, such as occurs during ejection from the vehicle'' (15).

Fractures of the first-rib have also been associated with fractures of the clavicle (16). In a study of 17 cases with both injuries, Weiner and O'Dell (16) found that all injuries occurred from violent traumatic incidents. There are two areas of the clavicle in particular that appear to have considerable weight on the forces that affect the first-rib: the attachment for the costo-clavicular ligament and the attachment for the subclavius muscle. The costo-clavicular ligament originates on the superior surface of the first costal cartilage and inserts on the inferior surface of the medial part of the clavicle. The subclavius muscle arises from the first-rib and its cartilage and inserts on the inferior surface of the clavicle. Injury to these areas of the clavicle often produce first-rib injuries. Additionally, *m. scalenus anterior, m. scalenus medius,* and *m. serratus anterior* may be important in the production of associated injuries of the clavicle and the first-rib (16). The two scalene muscles originate on the transverse processes of the cervical vertebrae and insert on the superior surface of the first-rib, while *m. serratus anterior* attaches the upper eight ribs to the scapula (17). These three muscles support the vertebral column in the neck and raise the rib cage during sharp inspiration. Severe contraction of these muscles may be important in the production of combined clavicular and first-rib injuries.

There are four postulated mechanisms of injury to the first-rib: (1) indirect violence, with the force transmitted through the clavicle, (2) direct violence, with the force applied from behind, (3) indirect violence, with the force transmitted through the manubrium, and (4) avulsion fracture produced by *m. scalenus anterior* (16).

First-rib fractures have also been associated with brachial plexus injuries. Brachial plexus is usually formed from the ventral primary rami of C5-C8 nerves and most of T1. Roots of the brachial plexus emerge into the neck between the middle and anterior scalene muscles and the C8 root passes between the first-rib and the clavicle (18,19). Therefore, fractures of the first-rib near the neck are often associated with brachial plexus injuries. Narakas (20) and Millesi (21) attribute the greatest frequency of brachial plexus injuries to motorcycle accidents (76% and 70%, respectively), followed by auto accidents (6% and 11%, respectively), and auto-pedestrian accidents (4% and 9%, respectively). In addition to first-rib fractures, fractures to the clavicle and humerus have been related to brachial plexus injuries (19). In particular, associated injuries include rib fractures, skull fractures, and upper extremity fractures. In one case the individual displayed fractures of the scapular body and the first and second ribs (22). The significance of brachial plexus injuries will be discussed later.

Scapula

Similar to first-rib fractures, fractures of the scapula are relatively rare (22–26), due to the great force required to disrupt the scapula. Fractures of the scapula are often associated with considerable violence (26), severe force (27–29), and violent trauma (25). Scapular fractures are therefore associated with wide impact trauma and often result from direct impact (25,27,28).

Overall, the greatest frequency of scapular fractures is associated with vehicular accidents. Thompson et al. (23) examined 58 scapular fractures in 56 individuals and found the most common mode of injury to be from motor vehicles (53.6%), followed by motorcycles (16.1%), auto-pedestrian accidents (14.3%), crushes (7.1%), and falls (5.3%). McGahan et al. (22) found a similar pattern with 52% resulting from automobile accidents, 18% from auto-pedestrian, 12% from falls, and 11% from motorcycle accidents. Armstrong and van der Spuy (29) examined 62 individuals with 64 fractures and found motor vehicle accidents to be the most prevalent, accounting for 32.3% of the injuries, followed by auto-pedestrian (24.2%), assault (14.5%), motorcycle-bicycle (8.1%), and train (8.1%).

The pattern of scapular fractures is unique in that the fractured scapula is often associated with other injuries, especially ipsilateral clavicle and rib fractures (22,23,28). Miller and Ada (27) found a high association of scapular injuries and upper thoracic rib fractures (96% concordance); however, McGahan et al. (22) only found associated rib fractures 44% of the time. Both studies found a 25 to 26% association with ipsilateral clavicular fractures. McGahan et al. (22) also found a 24% association with fractures to the skull.

There are three classes of scapular fractures: coracoid/acromion, glenoid, and major body, with injuries to the body being most common (22,23,27). Injuries of the glenoid neck are believed to result from the impact of the humeral head into the glenoid fossa

(23). Transmission of this force to the clavicle has been used to explain the high incidence of associated ipsilateral clavicular fractures. Additionally, most types of scapular fractures are caused by a crushing injury (26), while avulsion fractures are very rare (24). However, fractures of the inferior and superior angle are believed to be an avulsion type of injury (28).

Clavicle

Injury to the clavicle is most likely a result of direct trauma (4,27,30,31). A posteriorly directed force on the shoulder, or the scapula itself, may cause the clavicle to bend and break over the fulcrum of the first-rib, that is when the sternoclavicular joint is intact (27,32). The critical force that causes the clavicle to fracture depends on the speed at which the body impacts, as well as the weight of the body (4).

The pattern of clavicular fractures can be used to assess the nature of the injury. Fractures of the middle third have been attributed to falling on an outstretched hand or point of the shoulder, where a fall on the point of the shoulder transmits the body's weight through the clavicle (31). Fractures of the proximal end have been attributed to direct violence applied at an angle from the lateral side (4). Finally, fractures distal to the costo-clavicular ligament are a result of force on the point of the shoulder driving the humerus and scapula downward (4).

Vertebrae

The most common cause of injuries to the spine is motor vehicle accidents (45%), followed by falls (20%) (33), with vertebral body fractures most frequently occurring from T11 to L2 (~50%) (10). As mentioned earlier, this is partially a result of the decrease in rib restraint. With auto-pedestrian accidents, pedestrians had a high frequency of thoracic injuries (34).

There are several types of vertebral injury patterns, including lateral compression, shear force, flexion-distraction, and extension (10,35). Injury resulting from lateral compression is often limited to vertebral body fractures. As a result of shear force, traumatic anterior spondylolisthesis is more common. Shear force injuries are caused by a violent force directed across the long axis of the trunk.

Flexion-distraction injuries may occur as a result of ejection from a motor vehicle or a fall from height. These injuries cause tearing or avulsion of the bony vertebral elements, as well as discs and ligaments. The vertebral injury ''involves a horizontal fracture beginning in the spinous process and progressing through the laminae, transverse processes and pedicles and extending into the vertebral body'' (10). Extension injuries are caused by the posterior thrust of the head or upper trunk and may result in facet, laminae, and spinous process fractures (10).

Case Studies

In order to understand the mechanisms of injury associated with particular skeletal injuries, a sample of seven skeletons who suffered injuries related to being struck by a vehicle ($n = 6$) and falling from a height ($n = 1$) in the Documented Collection at the University of New Mexico was examined. Four individuals were struck by cars, one was struck by a truck, one was struck by a train, and one fell from a vehicle. Knowledge of the nature of injury for these individuals is used to assess whether there are characteristic patterns of injuries associated with a particular type of trauma.

Case #1: Pedestrian Struck by Train

This individual was a male in his twenties. He was struck by a train from the front. It is believed that the initial impact was from the metal framework on the front of the train to his head. Injuries sustained include extensive fracturing of the skull, including the frontal, parietals, and occipital, both tibiae and fibulae, and the left humerus, radius, and ulna. Additionally, the right scapula was fractured at the spine, body, and inferior and superior angles (Fig. 1). Fracture of the scapula is consistent with an injury sustained from great force and wide impact. While most scapular injuries are a result of a crushing force, fractures to the inferior and superior angles, as well as the spine, suggest an avulsion type injury.

As suggested in the literature, scapular injuries are often associated with ipsilateral rib fractures. There were numerous rib fractures to the right side, as well as the left. In fact, with the exception of the left third rib, both sides displayed fractures of the first through the ninth ribs. Areas of fracture included the sternal end, midshaft, and vertebral end, with the majority of fractures occurring at the vertebral end. While there were numerous rib fractures, the most notable were the fractures of both the first and second ribs near the vertebral end on both sides. Similar to fractures of the scapula, fractures to the first-ribs indicate extreme force, which is consistent with impact from a train.

Additionally, the left clavicle was fractured distal to the attachment for the costo-clavicular ligament, thereby suggesting that this fracture was the result of a force on the point of the shoulder driving the humerus and scapula down. Fractures of the clavicle are also associated with first-rib fractures.

There were also numerous fractures of the vertebral column. The first cervical vertebra suffered a fracture to the superior, anterior surface. Several thoracic vertebrae displayed fractured spinous processes (T2-T10), while several lumbar vertebrae displayed fractured transverse processes (L1-L4). Additionally, L5 displayed spondylolisthesis of the left side. Fractures of the spinous processes, laminae, and facets are consistent with an extension injury from the posterior thrust of the head, such as one would expect from an individual getting struck by a train from the front.

Fractures of the clavicle, humerus, and first-rib are also consistent with a brachial plexus injury, in which the C8 root runs over the neck of the first-rib. Other associated injuries include the ribs, skull, and upper extremity, all of which are observed in this individual. The numerous injuries sustained by this individual are expected considering the high speed and great force of the impact.

Case #2: Pedestrian Struck by Truck

This was a 77-year-old male who was struck by a truck on his right side while attempting to cross the highway. He was displaced 16 ft (5 m) after impact, which probably resulted in less severe injuries because of the dissipation of energy after impact. Because of this individual's age, there was significant fusion of bones, including the right os coxae and sacrum, several vertebrae, as well as several ribs to the vertebrae, and the first right rib to the manubrium. This individual did not suffer any cranial trauma. However, there were fractures to the right os coxae at the ischio-pubic ridge and the iliac blade.

The majority of injuries sustained by this individual were concentrated in the thoracic region. The right clavicle was fractured at the sternal end. Fractures of the sternal end have been attributed to direct violence applied at an angle from the lateral side (4). This is consistent with being struck on the right side. There was also a possible fracture to the left first-rib near the sternal end. There were

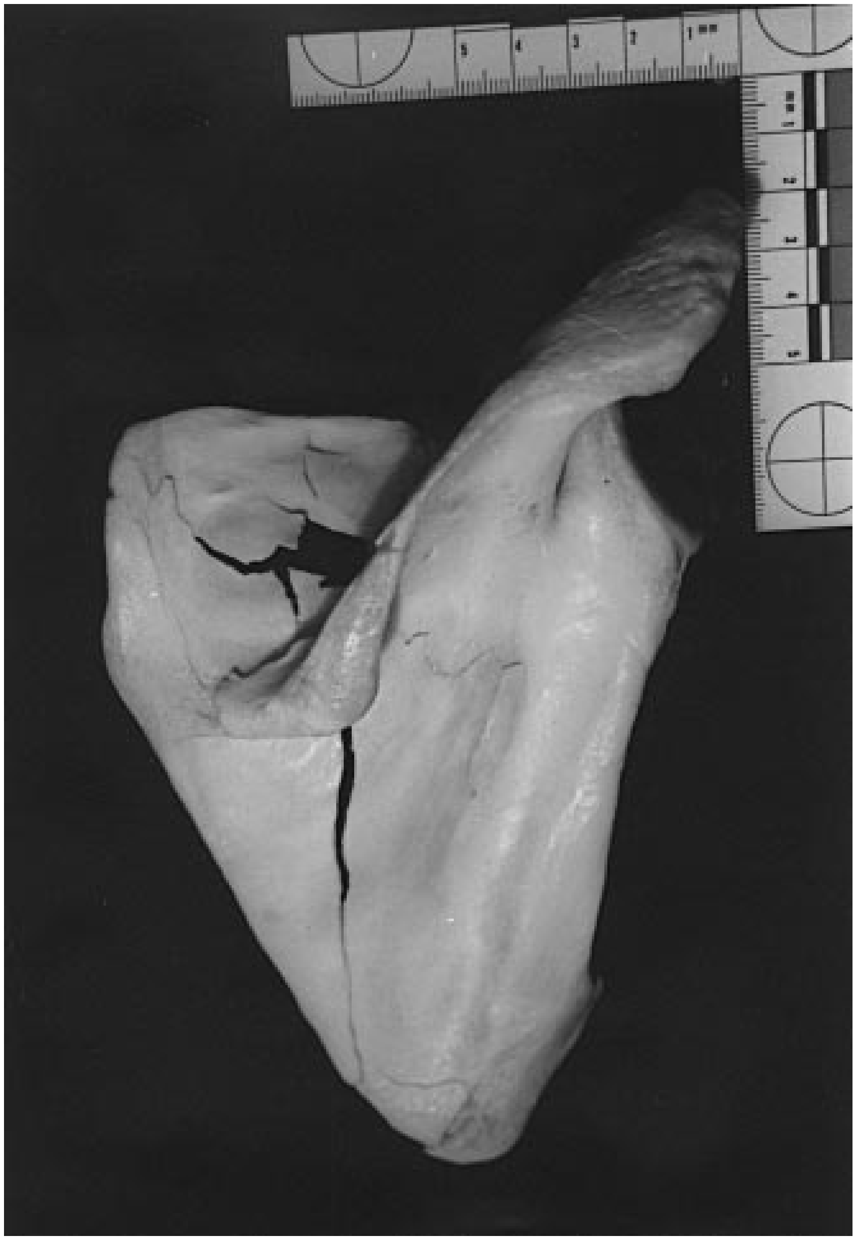

FIG. 1—*Fractured right scapula from Case #1. Fractures of the superior and inferior angles, as seen here, indicate an avulsion type of injury.*

additional fractures to five adjacent right middle ribs. However, because of the fragmentary nature of the remains, specific numbers could not be determined. The fractures occurred in the mid to mid/posterior shaft, with two of the ribs displaying at least two fractures. Multiple fractures to the mid to mid/posterior shaft of a rib indicate the application of a laterally directed force. The fact that these were adjacent ribs is consistent with a direct impact to the right side. Finally, there was a possible spinous process fracture to the twelfth thoracic vertebra. However, because of extensive destruction to the bone, a definitive conclusion is not possible.

Case #3: Pedestrian Struck by Car

This individual was an adult male who was struck from behind by a car. This individual suffered fractures to both os coxae, femora, tibiae, and fibulae. The right humerus and ulna were also fractured at the elbow joint. There was a fracture to the right scapular body, near the lateral/inferior border. Fracture to the scapula therefore implies a severe force was applied to this individual. Because of the high incidence of scapular fractures in vehicular-pedestrian accidents, this is not unexpected.

Additionally, there were numerous fractures to ipsilateral ribs, as well as contralateral ribs. The majority of rib fractures occurred at the vertebral ends, which is consistent with direct impact to the back. Both first-ribs were also fractured at the vertebral end, with the right first-rib also fractured at the sternal end.

There were also numerous vertebral fractures concentrated in the thoracic and lumbar region. Within the thoracic vertebrae there were fractures of the transverse processes (T1, T2, T3, T12) and compression fractures of the superior bodies (T4-T6). Additionally, there was a puncture wound on T2, just to the left of the spinous process. The first lumbar vertebra displayed a fracture of the spinous process and transverse processes, as well as the left superior articular facet. Additionally, the transverse processes of L2, L4, and L5 were fractured. These injuries are consistent with extension injuries caused by the posterior thrust of the head or upper trunk (i.e., getting struck from behind).

Case #4: Pedestrian Struck by a Car

This was a 36-year-old male said to have been struck from the front by a car. This individual suffered extensive cranial trauma, with fractures to the right frontal, parietal, temporal, sphenoid, and both zygomatics. Both tibiae and fibulae displayed multiple fractures, while the left femur displayed a hairline fracture on the distal, posterior surface of the shaft. There was a fracture of the right scapular body, thereby suggesting severe force. There were also several fractures of the vertebrae, including fractures of articular facets (C1, C7) and transverse processes (C7, T1, L4, L5). The spinous process of T11 was fractured and the sacrum was fractured. Fractures of the facets, laminae, and spinous processes are consistent with extension injuries, which implies that this individual was struck from behind. Additionally, there were fractures to the right ribs (R10, R12) near the vertebral ends, also suggesting that this individual may have been struck from the rear instead of from the front.

Case #5: Pedestrian Struck by a Car

This individual was an adult male. The bones for this individual were severely weathered, thereby making the assessment of fractures more difficult. There were multiple cranial fractures and multiple fractures of both tibiae and fibulae, as well as fractures on both femora and os coxae. The left humerus also displayed a fracture on the proximal shaft. The transverse processes of T4 were fractured, as well as other thoracic vertebrae. One right middle rib (R4-R10) was fractured at the vertebral end of the shaft, thereby indicating that this individual was possibly struck from the rear.

Case #6: Pedestrian Struck by a Car

This individual was an adult male who was struck from behind by a car. Similar to the other individuals struck by cars, this individual also suffered cranial trauma, including a fractured right temporal and zygomatic arch. The right femur and tibia displayed fractures along the shaft, while the right tibial plateaus were also fractured. In addition, both the right and left fibulae were fractured. The left scapular body and clavicle were fractured. The clavicle was fractured at the sternal end suggesting a direct force applied at an angle from the lateral side. The first cervical vertebra was fractured near the anterior facet for the dens and along the posterior arch. There were also several rib fractures, including fractures near the sternal end for the first three right ribs. There were several other middle ribs fractured on both sides, as well as the vertebral ends of R11 and R12. The pattern of rib fractures is consistent with getting hit from behind.

Case #7: Fell from a Vehicle

This was a 39-year-old male who sustained severe head injuries after falling from a vehicle. There were several cranial fractures, including both temporals, parietals and the right zygomatic. Additionally, there was a fracture of the first left rib, near the mid-shaft to the sternal end. There was also a fracture of a middle right rib (R4-R10) at the mid/vertebral end of the shaft. As stated earlier, in falls less than 40 ft (12 m), cranial trauma is most prevalent.

Results

As observed in these seven cases, fractures to the skull are common (5/7), with three out of the four individuals involved in pedestrian-car accidents displaying cranial fractures. While the first six cases represent horizontal deceleration injuries with all individuals displaying characteristic vertebrae and rib fractures, there appears to be a pattern with respect to the type of vehicle involved. For example, three out of the four individuals struck by cars suffered cranial fractures, and all four individuals suffered fractures to the lower extremities. However, the individual struck by the truck did not suffer any cranial trauma or lower extremity injuries.

All scapular injuries were unilateral, with four of the seven individuals displaying such fractures. Three out of the four pedestrians struck by cars suffered scapular fractures. Three of the four individuals that displayed scapular injuries also displayed ipsilateral first-rib fractures. However, in two of the three cases first-rib fractures were bilateral. Additionally, two of the three individuals with both scapula and first-rib fractures displayed fractures of the clavicle. The distribution of these injuries is presented in Table 1.

As evidenced in Table 1, there is no clear pattern found within this sample. However, there are numerous factors that contribute to this variation, including the direct area of impact and type of vehicle. While some individuals were struck from the side, others were impacted from the front or back. Another factor influencing the extent and nature of injury is the speed of the vehicle at impact. Despite the fact that the speed at impact is unknown for these cases, it is known to influence the extent and severity of injuries sustained. This overview supports the association of certain injuries with the position of the body to the vehicle at impact.

Examination of Case Study

Now that an understanding of some of the associated injuries with particular blunt trauma is attained, a thorough examination of the unknown case is undertaken. As mentioned earlier, this adult male suffered extensive injury to the thoracic region. The right scapula was fractured at the base of the spine, separating the supraspinous fossa from the remainder of the bone. There was also beveling of the fracture which indicates that the superior portion had either been pulled forward or the remainder of the scapula pulled away from this upper section (36), suggesting an avulsion fracture, which is very rare (24). This injury can most probably be attributed to contraction of the lower fibers of *m. serratus anterior.* As mentioned earlier, *m. serratus anterior* arises from the upper eight ribs, passes between the rib cage and the scapula and inserts along the entire length of the vertebral margin of the scapula (17). Contraction of the lower fibers of this muscle rotates the scapula upwards. However, a quick, severe contraction may result in the fracture at the areas of insertion. Therefore, it is possible that the contraction or displacement of *m. serratus anterior* may

TABLE 1—*Distribution of injuries sustained in the documented collection at the University of New Mexico.*

	Case #1	Case #2	Case #3	Case #4	Case #5	Case #6	Case #7
Scapula	right	no	right	right	no	left	no
1st Rib	both	left	both	no	no	right	left
Clavicle	left	right	no	no	no	left	no
Skull	yes	no	no	yes	yes	yes	yes
Vertebrae	yes	yes	yes	yes	yes	yes	no

have led to the fracture of the superior aspect of the body of the scapula. Because of the associated fracture to the area of attachment, the first-rib, contraction of *m. serratus anterior* seems the most probable cause for this injury. This type of scapular fracture, occurring at the base of the spine, was also observed in the individual who was struck by a train (Case #1), thereby suggesting the probable severity of impact.

The left clavicle of this individual was fractured 1/3 of the distance to the sternal extremity near the attachment for *m. subclavius* (36) (Fig. 2). Fractures of the middle third have been attributed to falling on an outstretched hand or point of the shoulder, where pressure on the point of the shoulder transmits the body's weight through the clavicle (31). However, fractures of the proximal end have also been attributed to direct violence applied at an angle from the lateral side (4). As stated earlier, a posteriorly directed force on the shoulder or the scapula itself may cause the clavicle to bend and break over the fulcrum of the first-rib, that is when the sternoclavicular joint is intact (27,32).

A fracture of the left clavicle is consistent with the fracture to the left first-rib; a similar pattern to that observed in the individual struck from behind by a car (Case #6). The left first-rib was fractured at the neck. Fracture of the posterior portion of the first-rib has been attributed to four different causes, including, (1) an indirect force transmitted through the clavicle, (2) a direct force delivered from behind, (3) transmission of force along the subclavius muscle to the anterior aspect of the first-rib, and (4) an indirect force transmitted through the manubrium (16). Because of the fracture to the ipsilateral clavicle at the attachment for *m. subclavius*, the first and third causes seem most probable. Also of import is that fractures of the first-rib near the neck are often associated with brachial plexus injuries. Traumatic injury to the brachial plexus may produce ''lethal hemorrhage from the subclavian artery or do serious harm to the roots of the brachial plexus'' (18). Therefore, it is possible that this individual died shortly after the incident, or was incapacitated from the injuries sustained.

Additionally, there is a fracture to the body of the right first-rib, just posterior to the dorsal subclavian groove in the region of attachment for the *m. scalenus medius* and *m. serratus anterior* (36). The scalenus medius muscle originates from the transverse processes of cervical vertebrae 5 through 7. Contraction of this muscle is associated with a lateral thrust of the neck and may have produced a fracture similar to the one observed. The fracture to the right first-rib may be associated with the scapula fracture and the contraction of *m. serratus anterior*. Ipsilateral scapula and first-rib fractures are also observed in Cases #1 (hit by a train), #3, and #6 (hit from behind by cars). As mentioned earlier, the serratus anterior muscle arises from the upper eight ribs, including the superior surface of the posterior one-third of the first-rib. Therefore, the contraction or displacement of *m. serratus anterior* may have led to the fracture of the superior aspect of the body of the scapula, as well as the fracture of the right first-rib. It should also be noted that injuries that lead to acromio-clavicular separation may result in the subclavius muscle transmitting an indirect force to the costal cartilage and the anterior portion of the first-rib, thereby producing a fracture of the posterior portion of the first-rib (36), as is observed on the right side.

Fractures to the first and second ribs on both sides support this individual having experienced a severe force. Several of the individuals in this study also displayed first-rib fractures, including Cases #1 (hit by a train), #2 (hit by a truck), #3 and #6 (hit from behind by cars).

In addition to fractures of the first-ribs, there are fractures to left ribs 3–12 at the vertebral ends. Additionally, the sternal ends of left ribs 5–9 are fractured. Rib fractures near the spine and sternum have been associated with forces applied from the side. Because of the fractures of adjacent ribs on the left side, the injuries sustained are consistent with a single episode of trauma to the left side.

There are also numerous fractures within the lower thoracic vertebrae (T7-T12), as well as fractures of T4 and L1. Fractures of articular facets are found in T4, T7, T8, T10, and L1. There is also wedge-shaped separation of the superior-anterior aspects of T7-T8 vertebral bodies. This patterning, as well as articular facet fractures imply rotation and forward-directed pressure (36). Additionally, fractures of the spinous processes (T7-T10), transverse processes (T8-L1), and portions of the vertebral bodies (T8, T9, L1) indicate avulsion fractures (Fig. 3). Fractures of the spinous processes, laminae, and transverse processes may also indicate rotation, as these areas of fracture are sites of attachment for the main rotators of the back, the transversospinalis muscles. These muscles include *m. semispinalis*, *m. multifidus*, and *m. rotatores* and run from the transverse processes and laminae to the spinous processes of supe-

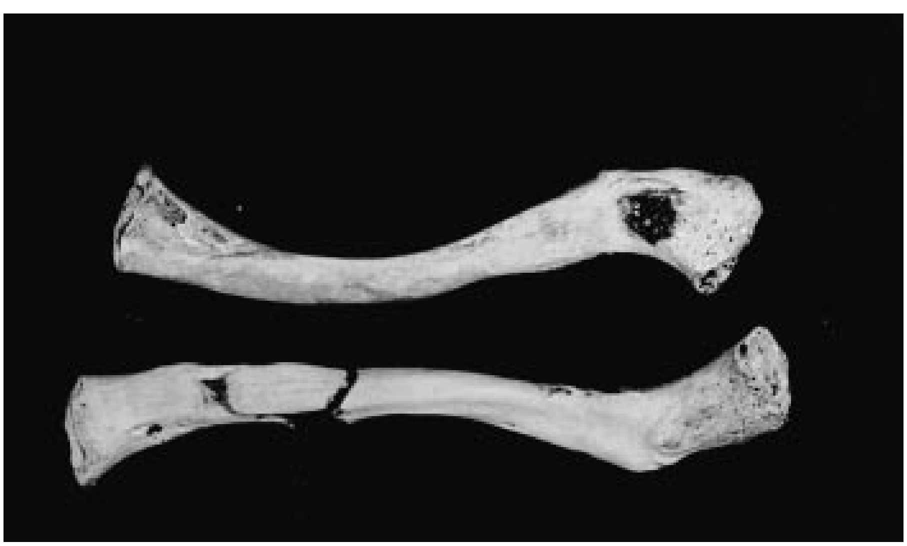

FIG. 2—*Fracture of the left clavicle in the case study.*

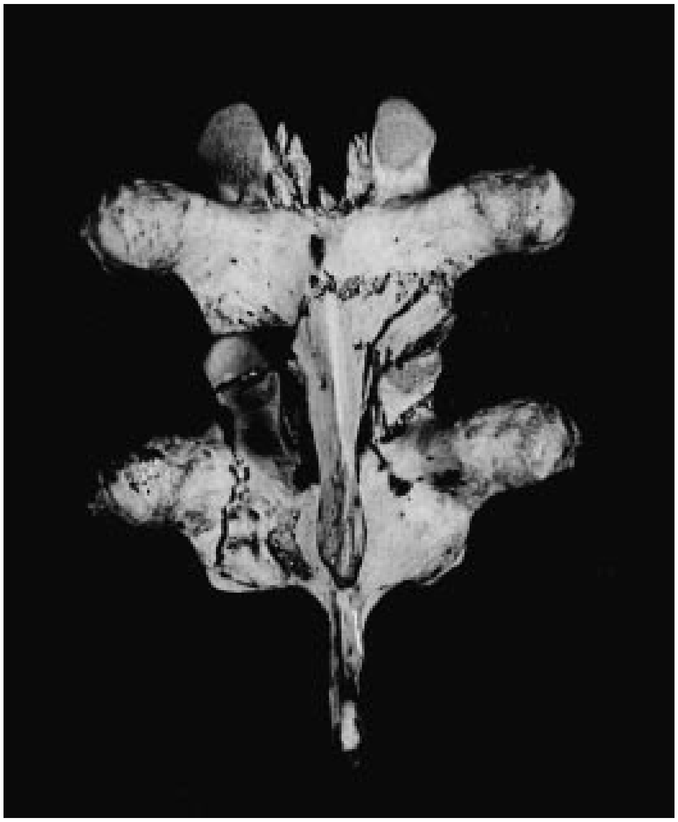

FIG. 3—*Fractures of spinous process, transverse processes, and articular facets in the case study. These injuries suggest avulsion fractures.*

rior vertebrae. Each muscle acts to rotate the back, but vary in number of vertebrae they cross before insertion and area of greatest development. For example, *m. rotatores* is most developed in the thoracic region where rotation is the principal movement of the spine (17) and where most of the injuries occurred in this individual. Therefore, rotation and forward-directed pressure from the left side may have caused violent contraction of these muscles, thereby explaining the fracture pattern observed. The pattern of vertebral fracture indicates that a force was applied from the rear.

Discussion

The pattern of injuries sustained by this individual is consistent with a direct impact from the rear, focused on the left side. This conclusion is supported by the similar fracture patterns observed in individuals struck from behind by vehicles examined in this study. Avulsion fractures of the spinous processes, transverse processes, and articular surfaces suggest an extension injury caused by the posterior thrust of the head or upper trunk, which would result from an impact from behind. However, fractures of several adjacent left ribs, the left clavicle, and left first-rib suggest that the impact was directed from the left side. In addition, this extreme force to the left side may have produced the avulsion fracture of the right scapula. Contraction of *m. serratus anterior* and acromioclavicular separation, therefore, could have produced the fracture to the vertebral portion of the first right rib. Therefore, the pattern of injuries to the thoracic region of this individual is most consistent with a severe impact applied from the left side of the back.

The nature of the injuries sustained and the location of the body upon discovery suggest two possible scenarios to explain the extensive trauma suffered by this individual: (1) This individual fell backwards from a treehouse (~20 ft (6 m) aloft) onto a soft substrate in the wooded area, walked approximately 100 yd (91 m) (37) and lay down under a fallen tree in a ''face-down'' position (Fig. 4). Or (2), this individual was struck by larger vehicle, like a truck, and transported to the area where the body was hidden under a tree.

The absence of cranial, upper vertebral, and upper extremity trauma, as well as the position of the body, do not support the scenario that this individual fell from a height. Because of the prevalence of injuries to the skull, forearm, and cervical vertebrae in vertical deceleration injuries less that 40 ft (12 m), the injuries sustained by this individual cannot be attributed to a low fall. While the probability of fractures to the chest, pelvis, and thoracic vertebrae increases with higher falls (over 40 ft (12 m)), the probability of injuries to the lower extremities also increases. Because of the absence of fractures to the pelvis and lower extremities, as well as the improbability of this individual falling from a height exceeding 40 ft (12 m) in a wooded area, it seems unlikely that the injuries sustained by this individual, at or around the time of death, are directly related to a fall from a height.

Also, the position of the body upon discovery (face down, partially under a fallen tree) suggests that this individual would have either fallen face down, or moved to that position after the fall. Because a natural response when falling is to extend one's arms to ''break'' a fall, fractures of the upper extremity are expected. The absence of such injuries suggests that this individual probably did not fall face down, which would be consistent with the position in which the body was found. Additionally, the position of the body upon discovery is not consistent with any other type of fall (i.e., backward fall).

The location of the treehouse, the only place this individual could have fallen from, in relation to the body upon discovery (approximately 100 yd (91 m)), removes the possibility that this individual fell to his death at the location of where the body was discovered. Additionally, movement by this individual after the fall to the discovered position is unlikely due to the nature of his injuries. The nature of his fractures most likely resulted in injury to the brachial plexus and the subclavian artery. Such injuries would have severely limited movement after the fall, if not resulted in death soon after.

The absence of cranial and lower extremity trauma is inconsistent with being struck by a smaller vehicle. However, this individual displayed similar fracture patterns to individuals struck from behind. This individual suffered extensive trauma to the thoracic region, consistent with a severe impact applied to the left side of the back. These injuries are consistent with Case #2, where the pedestrian was struck by a larger vehicle, a truck. While fractures to the skull and lower extremities were not observed, injuries to the thoracic region were characteristic.

Although the first scenario may seem more parsimonious, considering the body was discovered in the wooded area, the injuries are more characteristic of a horizontal deceleration injury. Additionally, the position of the body under the tree suggests that the body was placed there, rather than falling there or self-generated movement to the location.

Conclusion

The presence of injuries to relatively rarely fractured bones (scapula and first-ribs) suggests a wide, blunt trauma of extreme force. The pattern of fracture seen in the vertebral column suggests that

FIG. 4—*Position of body upon discovery in wooded area.*

the area of impact was the mid-back region, focused on the left side. This is consistent with avulsion fractures of the spinous processes, transverse processes, and articular surfaces, as well as fractures to several adjacent left ribs, the left clavicle, and the left first-rib. A quick contraction or displacement of *m. serratus anterior* caused by this extreme force, may have resulted in the avulsion fracture on the scapula. This contraction may also have produced acromioclavicular separation, and as a result, fracture of the ipsilateral first-rib. Although death by a vehicle necessitates transportation of the body to a secondary area, the pattern of injuries to the thoracic region of this individual is most consistent with a severe impact trauma, probably a truck, applied to the left side of the back.

That a fall from the nearby treehouse could have led to this fracture pattern is unlikely, as is hypothesized self-generated movement of the body due to the severe nature of the injuries. We believe the injuries are most consistent with vehicular trauma—most likely a truck striking a pedestrian from behind, on the left side.

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References

1. di Maio DJ, di Maio VJM, editors. Forensic Pathology. New York: Elsevier, 1989.
2. Maull K, Whitley R, Cardea J. Vertical deceleration injuries. Surg Gynecol Obstet 1981;153:233–6.
3. Gupta SM, Chandra J, Dogra TD. Blunt force lesions related to the heights of a fall. Am J Forensic Med Pathol 1982;3:35–43.
4. Allman FL. Fractures and ligamentous injuries of the clavicle and its articulation. J Bone Joint Surg Am 1967;49-A:774–84.
5. Harkness JW, Ramsey WC, Ahmadi B. Principles of fractures and dislocations. In: Rockwood CA, Green DP, editors. Fractures in adults. Vol 1. Philadelphia: JP Lippincott Company, 1984;1–180.
6. Hipp JA, Cheal EJ, Hayes WC. Biomechanics of fractures. In: Browner BD, Jupiter JB, Levine AM, Trafton PG, editors. Skeletal trauma. Philadelphia: WB Saunders Company, 1992;95–126.
7. Lewis WS, Lee AB, Grantham SA. ''Jumpers syndrome.'' the trauma of high free fall as seen at Harlem hospital. J Trauma 1965; 5:812–8.
8. Simonsen J. Injuries sustained from high-velocity impact with water after jumps from high bridges. Am J Forensic Med Pathol 1983;4:139–42.
9. Scalea T, Goldstein A, Phillips T, Sclafani SJA, Panetta T, McAuley J, et al. An analysis of 161 falls from a height: the 'jumper syndrome.' J Trauma 1986;26:706–12.
10. Eismont FJ, Garfin SR, Abitbol JJ. Thoracic and upper lumbar spine injuries. In: Browner BD, Jupiter JB, Levine AM, Trafton

PG, editors. Skeletal trauma. Philadelphia: WB Saunders Company, 1992;729–804.
11. Goonetilleke A. Injuries caused by falls from heights. Med Sci Law 1980;20:262–75.
12. McConnell TS, Zumwalt RE, Wake J, Haihal N, McFeeley PJ. Rare electrocution due to powerline contact in a hot-air balloon. J Forensic Sci 1992;37:1393–1400.
13. Shkrum MJ, Green RN, Novak ES. Upper cervical trauma in motor vehicle collisions. J Forensic Sci 1989;34:381–90.
14. Tonge JI, O'Reilly MJJ, Davison A, Johnston NG, Wilkey IS. Traffic-crash fatalities (1963–73): injury patterns and other factors. Med Sci Law 1977;17:9–24.
15. Mulligan GWN, Pizey GS, Lane D, Anderson L, English C, Kohut C. An introduction to the understanding of blunt chest trauma: the human thorax—anatomy, injury, and biomechanics. Dearborn: Society of Automotive Engineers, 1976.
16. Weiner DS, O'Dell HW. Fractures of the first-rib associated with injuries to the clavicle. J Trauma 1969;9:412–22.
17. Aiello L, Dean C. An introduction to human evolutionary anatomy. London: Academic Press, 1990.
18. Mathers LH, Chase RA, Dolph J, Glasgow EF, Gosling JA. Clinical anatomy principles. St. Louis: Mosby, 1996.
19. Wilgis EFS, Brushart TM. Brachial plexus and shoulder girdle injuries. In: Browner BD, Jupiter JB, Levine AM, Trafton PG, editors. Skeletal trauma. Philadelphia: WB Saunders Company, 1992; 1311–26.
20. Narakas AO. The treatment of brachial plexus injuries. Int Orthop 1985;9:29–36.
21. Millesi H. Surgical management of brachial plexus injuries. J Hand Surg 1977;2:367–79.
22. McGahan JP, Rab GT, Dublin A. Fractures of the scapula. J Trauma 1980;20:880–3.
23. Thompson DA, Flynn TC, Miller PW, Fischer RP. The significance of scapular fractures. J Trauma 1985;25:974–7.
24. Ishizuki M, Yamaura I, Isobe Y, Furuya K, Tanabe K, Nagatsuka Y. Avulsion fracture of the superior border of the scapula. J Bone Joint Surg Am 1981;63-A:820–2.
25. Zdravkovic D, Damholt VV. Comminuted and severely displaced fractures of the scapula. Acta Orthop Scand 1974;45:60–5.
26. Edeland HG, Zachrisson BE. Fracture of the scapular notch associated with lesion of the suprascapular nerve. Acta Orthop Scand 1975;46:758–63.
27. Miller ME, Ada JR. Fractures of the scapula, clavicle, and glenoid. In: Browner BD, Jupiter JB, Levine AM, Trafton PG, editors. Skeletal trauma. Philadelphia: WB Saunders Company, 1992; 1291–1310.
28. Imatani RJ. Fractures of the scapula: a review of 53 fractures. J Trauma 1975;15:473–8.
29. Armstrong CP, Van der Spuy J. The fractured scapula: importance and management based on a series of 62 patients. Injury 1984;15: 324–9.
30. Fowler AW. Fracture of the clavicle. J Bone Joint Surg Br 1962; 44-B:440.
31. Sankarankutty M, Turner BW. Fractures of the clavicle. Injury 1975;7:101–6.
32. Stanley D, Trowbridge EA, Norris SH. The mechanism of clavicular fracture. J Bone Joint Surg Br 1988;70-B:461–4.
33. Keenen TL, Bensen DR. Initial evaluation of the spine-injured patient. In: Browner BD, Jupiter JB, Levine AM, Trafton PG, editors. Skeletal trauma. Philadelphia: WB Saunders Company, 1992; 585–604.
34. Horowitz R, Siegel J, Flaster M, Maldonado WE. Injury patterns in motor vehicle fatalities. J Forensic Sci 1987;32:167–72.
35. Levine AM. Lumbar and sacral spine trauma. In: Browner BD, Jupiter JB, Levine AM, Trafton PG, editors. Skeletal trauma. Philadelphia: WB Saunders Company, 1992;805–48.
36. Buikstra JE, Hoshower L. McHenry County Case 04-03094 #67 Forensic Case Report. Chicago: University of Chicago, 1994.
37. McHenry County Sheriff's Department Case Report. McHenry County, IL, 1994.

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