THE BIOMECHANICS OF SPINAL COLUMN FAILURE

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Spinal failure is a manifestation of the spine's inability to resist a load that is placed upon it. The failure potential is related to the magnitude of the force, the bending moment that is created by this force and the intrinsic strength of the spine.

The etiologic factors of spinal failure can be broken into two main categories: traumatic and non-traumatic factors. Non-traumatic factors (tumor, degenerative disease, infection) affect the spinal column in different ways. However, all of them result in a reduction of load resisting abilities of the spinal column; i.e., the spinal column becomes prone to loading injuries. In this regard, all the etiologic factors affect the spinal column in a similar manner. Trauma is therefore discussed here as the 'model' etiologic factor of spinal column failure. Other etiologies are assumed, as mentioned, to affect the spinal column similarly.

Upper Cervical Spine

The upper cervical spine differs from all other regions of the spine. It harbors special anatomic characteristics, is the most flexible region of the spine, and is associated with a high incidence of exposure to severe trauma. These characteristics of the upper cervical spine make it prone to traumatic injuries. Usually, most upper cervical spine injuries are due to severe head injury (6,12,14,18,21). However, there are exceptional injuries that result from a deceleration, with an accompanying restriction of cervical spine movement. This can cause a flexion or distraction force application to the head and upper cervical spine (1).

With severe head injury, brain damage is a common cause of death. However, the disruption of upper cervical spine structures may also cause death via spinal cord injury or vascular disruption (4).

Factors Affecting Injury Type

The most important factor that determines the type of injury incurred is the orientation of the force vectors acting upon the spine. Force vectors via head injury affect the upper cervical spine by imparting loads through:

1) The odontoid process (via the ventral arch of C1 or the transverse ligament of C1), or

2) via true axial load application, (where the lateral masses of C1 and C2 bears the entire load) (Figure 1).

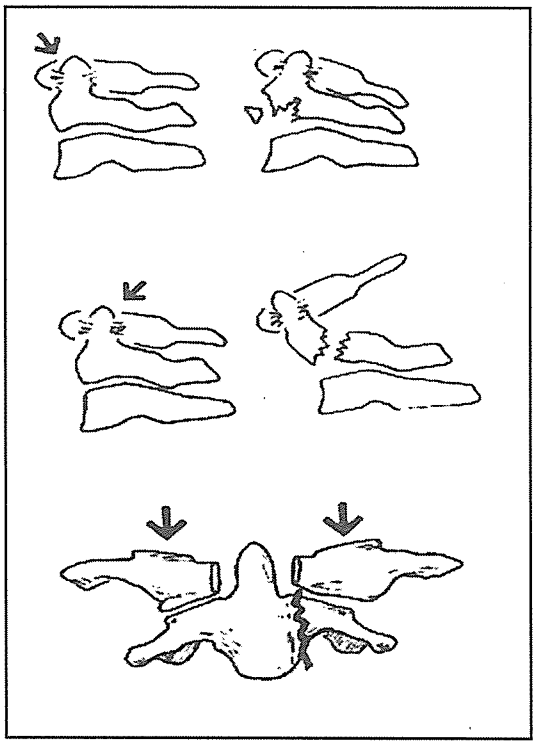

Figure 1. Blows to the head may cause an extension load A) or a flexion load B) to be applied via the odontoid process. However, if a true axial load is applied C), the lateral masses bear this load. In each case, if applied force is great enough, a fracture may result.

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The orientation of these force vectors determines the mechanism of injury (2) The injury mechanism and intrinsic strength properties of the spine determines the resultant injury type. Theoretically, when an axial load (to failure) is applied to the cervical spine, the possible resultant injuries are a C1 burst fracture, a C2 burst fracture, a subaxial cervical spine burst fracture or any combination of these. The intrinsic properties of each level play a major role in determining which resultant injury will occur. Usually C1 ring and subaxial cervical spine vertebral bodies are the weakest links. Therefore, a C1 burst fracture (Jefferson fracture) or any subaxial cervical spine burst fracture occurs.

Loss of Structural Integrity of the Subaxial Cervical, Thoracic, and Lumbar Spine

The anatomic features of these regions are biomechanically similar to each other. Therefore, they are discussed as a group.

Ventral Wedge Compression Fracture

When an axial load is placed ventral to the Instantaneous Axis of Rotation (IAR), the bending moment is also oriented ventrally. Vertebral body collapse is asymmetrical, resulting in a ventral wedge compression (Figure 2) (5,14,15,20).

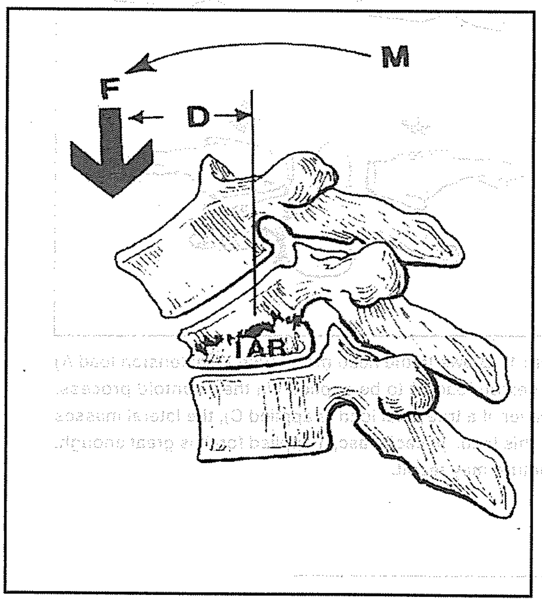

Figure 2. If a force vector is applied ventral to the IAR, the resultant failure is a ventral wedge compression fracture. F=applied force vector, D=length of moment arm, and M=bending moment.

This type of fracture usually occurs in the mid-low cervical, thoracic and thoracolumbar junction regions. The reason for the thoracic and thoracolumbar junction preponderance is the associated kyphotic curvature. A kyphotic curvature causes the spine to accept axial loads ventrally; and, thus there is a flexion component to most injuries caused by a ventrally oriented bending moment.

The cervical spine has natural lordotic posture. However, often at the time of load application, it is oriented in flexion. This makes this region prone to ventral wedge compression fractures as well. This also explains why ventral wedge compression fractures are more common in the cervical spine than the lumbar region. The mid-low lumbar spine does not usually assume a flexed posture during axial loading. Therefore, a wedge compression fracture-inducing bending moment is not created. If the cervical spine maintains its natural lordotic posture during the application of an axial load, there is no bending moment applied. A burst fracture, therefore may occur as a result (Figure 3).

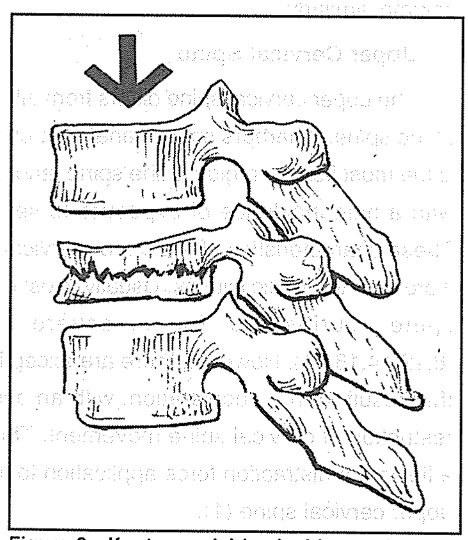

Figure 3. If a true axial load without a bending moment (d=0) is applied, the resultant failure is a burst fracture.

The lumbar region has an intrinsic lordotic posture with massive vertebral bodies. Therefore, the orientation of force application is usually true axial loading.

Burst Fractures

If a true axial load (to failure) is applied to the subaxial spine, the force vector passes through the IAR. The length of the moment arm related to this force vector is zero (perpendicular distance from the force vector to the IAR). With such a load application, there is no bending moment. The vertebral body collapses symmetrically, and a true burst fracture results (Figure 3) (5,8,9,14, 15,16,17).

The retropulsion of bone and/or disc fragments into the spinal canal is a feature of true axial loading. This alone defines a burst fracture, as per Denis (10). It is not, however, a criteria for such here. Only the mechanisms of injury, from a kinematic and biomechanical perspective are considered.

Burst fractures usually occur in the upper and mid-cervical and mid-low lumbar regions. This is due to their requirement for true axial loading. In the upper and mid-cervical spine, the relatively less lordotic posture makes this region prone to burst fractures. In low lumbar region, burst fractures are less common than the upper and mid-lumbar region because of a greater lordotic posture and the relatively large size of vertebral bodies in this region. Although the cervical spine (upper- to mid) is prone to burst fractures, in clinical practice wedge compression fractures occur more frequently than burst fractures. This is due to the high flexibility of the cervical spine that causes the cervical spine to accept loads in a flexed position.

Lateral Wedge Compression Fractures

Discussions regarding burst fractures and wedge compression fractures usually focuses upon sagittal plane deformation. However, along with sagittal plane deformities, there can be associated coronal plane deformities. The injury mechanism of lateral wedge compression fractures is the same as with ventral wedge compression injuries. The only difference is location of the application of the axial load and the orientation of the moment arm (Figure 4).

Following the application of an axial load, the spine may 'buckle'. This buckling may result in lateral bending (Figure 5), which cause vertebral body deformation in the coronal plane. This buckling effect may also occur in the sagittal plane and thus may cause a sagittal plane compression fracture.

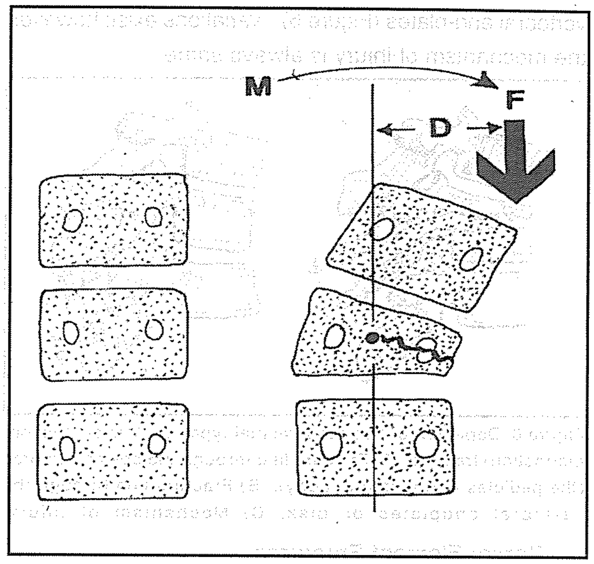

Figure 4. In a coronal plane, eccentrically applied loads cause bending of the spine. If failure of the vertebral body occurs, it will be oriented in the same direction with bending. F=eccentrically applied force, D=length of moment arm, M=bending moment.

Flexion - Distraction (Chance) Fracture

All fracture types discussed so far have an axial load component of the injury mechanism. However, distraction may occasionally play a role. The most common cause of this type of injury is a deceleration motor vehicle accident, in which one is wearing a lap belt without a shoulder harness. In such a circumstance, there is restriction of pelvic and lumbosacral movement, with unrestricted distraction and forward flexion of the spine (flexion with forward bending). This type of injury is known as a Chance fracture (7,13,19).

This injury may be classified into two basic types: 1) a diastasis (fracture line) through the pedicles, lamina, and vertebral body; and 2) a fracture line through the

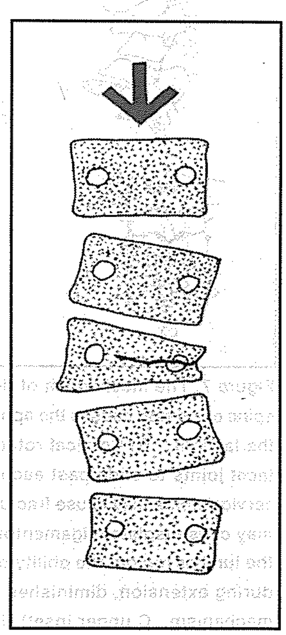

Figure 5. The 'buckling' of the spine secondary to axial loading.

vertebral end-plates (Figure 6). Variations exist; however, the mechanism of injury is always same.

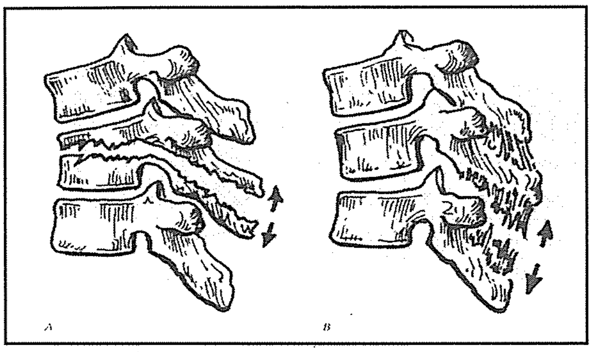

Figure 6. Depiction of two fundamental types of Chance (flexion-distraction) fracture. A) Fracture line through the bony structures (the pedicles and vertebral body). B) Fracture line through the vertebral endplates or disk. C) Mechanism of injury.

Dorsal Element Fractures

With the fractures discussed so far, the force vector is situated at or ventral to the IAR. However, in the cases in which an axial load is located dorsal to the IAR, compressive forces are applied to the dorsal elements of the spine. This places the spine at risk for dorsal element failure (Figure 7).

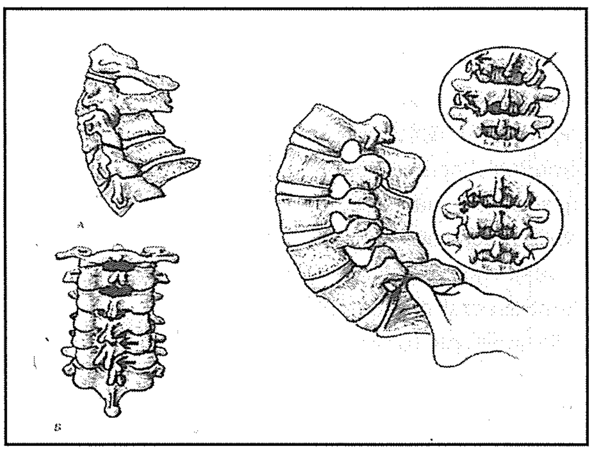

Figure 7. The mechanism of dorsal elements injury. A) Cervical spine extension causes the approximation of the facet joints and/or the laminae. B) Cervical rotation causes the coronally oriented facet joints to slide past each other. While the extension of the cervical spine may cause fracture, the rotation of the cervical spine may cause isolated ligamentous disruption or dislocation. C) In the lumbar region, the ability of facet joints slide past each other during extension, diminishes the chance of facet failure by this mechanism. C upper inset) However, lumbar rotation results in one facet abutting against another and may result in facet fracture. C lower inset) Conversely, extension or flexion causes the sagittally oriented facet joints to slide past each other.

In clinical practice, the incidence of dorsal element fractures is common. In particular, the cervical spinal region is prone to this type of injury. The natural lordotic posture, the small size of vertebral segments, and the intrinsic flexibility contribute to this. Although, the lumbar region also has natural lordotic posture, the massive size of vertebral segments, the more protective affects of the paraspinous muscles in this region, and the sagittal orientation of the facet joints diminishes the chance of dorsal element fractures in this region. Furthermore, this region is less flexible than the cervical spine.

Extension of the cervical spine forces the opposing facet surfaces to come into close contact. This leads to significant stress being placed on the facets and pars interarticularis (Figure 7a). Conversely, rotation of the cervical spine causes the facet surfaces to slide by each other, without being stressed (Figure 7b). Fractures of lumbar spine dorsal elements are usually associated with other injuries (e.g., compression fractures, rotational injuries, translational injuries). The magnitude of the rotatory force that results in injury of the facet joints is usually enough to produce vertebral body fracture or disc interspace disruption at the same time. They are uncommon because of the diminished flexibility of the spine and the vertical orientation of facets in this region. A severe hyperextension injury may cause lamina and/or pars interarticularis fractures (5). The relative restriction of rotation of the lumbar spine minimizes the chance of facet joint injury due to rotation. Finally, excessive cervical flexion may cause interspinous ligament injury and excessive lateral bending of the lumbar spine may cause fractures of transverse processes on the convex side of the bend (Figure 8).

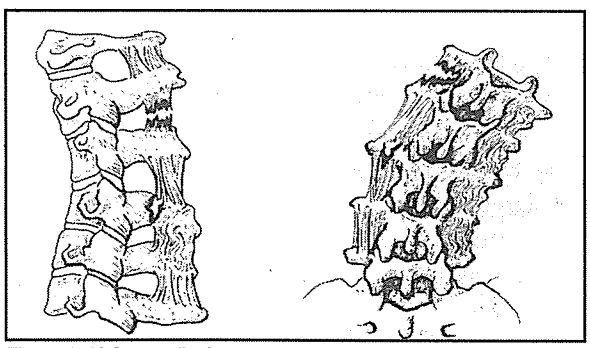

Figure 8. A) Severe flexion may result in spinous process fractures or ligamentous disruption. B) Excessive lateral bending may cause a transverse process fracture or ligamentous disruption.

Ligamentous Injuries

Ligamentous injuries may occur in cervical spine as isolated entities. However, in the lumbar spine, they usually occur in combination with bony disruption. MRI (especially T2 weighted images) is very sensitive for soft tissue injuries (3).

The flexibility of the cervical spine causes substantial strain to be placed on the ligaments. This makes the ligaments prone to injury. The more massive and less flexible lumbar spine does not depend on ligamentous support as much as the cervical spine. The lumbar spine (especially the lower lumbar spine) dorsal ligaments (especially the interspinous and supraspinous ligaments) are usually weak or absent. Therefore, dorsal ligamentous injuries do not occur as an isolated injury in this region.

Facet Dislocation

Facet dislocation usually occurs in the cervical, and to a lesser extent, in the upper thoracic region because of the coronal orientation of the facet joints. In these regions, excessive flexion may cause the normal range of facet joint mobility to be exceed. This results in facet failure by fracture, perching, or locking (Figure 9 a, b and Figure 10).

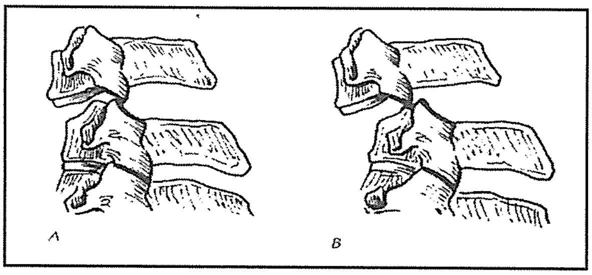

Figure 9. Cervical spine facet injuries. A) perched, and B) locked.

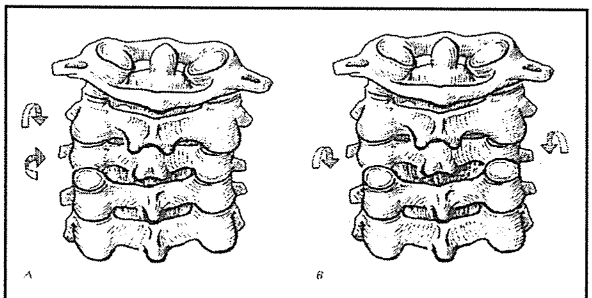

Figure 10. A) Flexion plus rotation (curved arrows) causes unilateral cervical facet joint dislocation. B) Pure flexion (curved arrows) causes bilateral facet joint dislocation.

In this situation, there are several force vectors acting on the facet joints. The most important of these is true flexion, which often causes bilateral facet dislocation. If a flexion moment is combined with a rotational component, a unilateral facet dislocation may result (Figure 10). These types of injury mechanisms or excessive hyperextension, combined with axial loading, may cause facet fractures.

Loss of Structural Integrity of the Sacrum and Surrounding Bony Elements

Sacral fractures usually occur in combination with disruption of the pelvic ring in at least one or more additional locations. Fractures of the sacrum may be grouped into vertical and horizontal types. The sacrum can be divided into three zones. Considering this, fractures of the sacrum are grouped into three types (11).

Zone 1 injuries usually involve vertical fractures of the ala and do not involve the neuroforamina. Usually, lateral compression forces are the mechanism of injury. If there is no significant translational deformation, this type of fracture is considered stable. Zone 2 injuries also involve vertical fractures, but additionally they involve the ventral neuroforamina. Zone 3 injuries include a vertical and a horizontal component. Therefore they involve the sacral spinal canal. There is nearly always an associated neurologic injury (especially bladder dysfunction) (Figure 11).

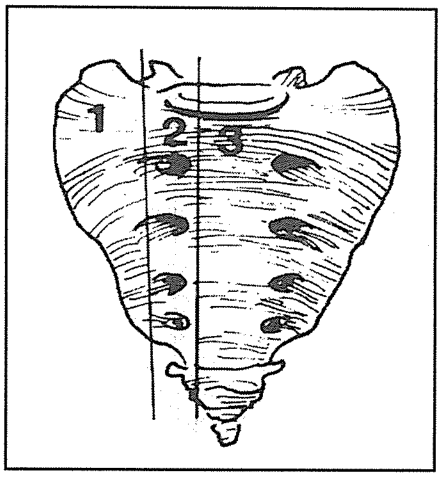

Figure 11. Depiction of three zones, or injury patterns of sacral fractures.

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