

Compression Injuries of the Cervical Spine: A Biomechanical Analysis

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Three intact cadavers and 10 isolated cervical spinal columns underwent compression, with forces directed vertically, forward, or rearward. Failure modes were often different than force directions. The loads required to produce bony injury or ligamentous disruption ranged from 645 to 7439 N. Flexion and extension injuries were produced at approximately 50% of the loads required for axial compression failures. The direction of force delivery correlated only partially with the resulting pathological condition. Clinical decisions based on retrospective analysis of roentgenograms may not account for the variability of forces and the prominence of ligament injuries seen in spinal trauma. Some of the difficulties encountered in biomechanical analyses of spinal trauma are discussed. (*Neurosurgery* 13:254-260, 1983)

Key words: Cervical spine, Compression injury, Ligament injury, Spinal trauma, Spine biomechanics, Spine fracture

INTRODUCTION

Injuries produced by compression loads, delivered either axially or in association with flexion or extension, represent the majority of cervical spine injuries observed in most centers (1, 4). Spinal cord compromise is often due to bone, disc, or ligament fragments in the vertebral canal (4). Despite a thorough history and physical examination, it is difficult to determine the injury force vectors. Soft tissue trauma to the head may be misleading because it is often due to secondary impact after spine injury. Furthermore, cervical cord trauma has been demonstrated without craniocervical contact (7, 16) and is not unusual in the absence of radiographic evidence of spine fracture (12).

The clinical biomechanics of compression injuries have been studied extensively, primarily on the basis of roentgenogram review (1, 2, 4, 5, 7, 10, 20). Briefly, axial impact in the absence of rotation is suggested as a cause of burst fracture of the vertebral bodies. These forces are often associated with the Jefferson fracture of C-1, with propulsion of the lateral masses and posterior dislocation of the arch. When failure occurs in the lower cervical spine, the intervertebral disc is often traumatized with compression of the nucleus pulposus into the vertebral body causing its fracture; further compression pushes the disc and vertebral body fragments anteriorly and posteriorly, the latter into the spinal canal (20).

In flexion-compression injuries, the forces are considered to be directed primarily to the vertebral bodies and intervertebral discs of the lower cervical spine (1). Anterior wedging of the body often occurs with or without significant fracture elsewhere. Dislocation may occur with column buckling or shear delivered transverse to the spinal axis (3, 6, 11, 16, 17). Rotational components often produce dislocations and/or fractures of the facets and associated ligamentous injuries (16).

Hyperextension injuries may also occur in association with compression. Characteristically, traumatic forces applied to the face are considered to be directed to the posterior elements through the atlas, and therefore multiple level abnormalities are often observed in the pedicle, facet, lamina, and spinous process (1, 6, 17, 20). If the forces are directed to the sagittal plane, bilateral lesions may be seen. More commonly, some rotation is present, and disruption of the facets is prominent.

In the presence of marked hyperextension, anterior ligamentous disruption, vertebral avulsion, and dislocation may occur. The latter occurs as the forces produce posterior translation of the head and upper cervical spine, with nearly complete ligamentous disruption (8).

Radiographic and mechanistic evaluation of the ligaments is particularly important because these structures are crucial in maintaining spinal stability. King and Vulcan suggested that ligamentous failure is not related directly to compression, but to distraction and shear forces (8). Similar suggestions have resulted from distraction studies done by others (15). As multiple forces are involved in most injuries, analyses should include evaluations of all components. The establishment of standards for force/trauma relationships and the development of appropriate models may aid in the amelioration of spinal injuries, especially those due to vehicular crashes (7). The present studies were conducted to analyze the spinal trauma produced by compression forces applied to the fresh human cadaver.

METHODS

Studies were carried out within 3 days of death in 13 unembalmed male cadavers. The specimens were free of bone disease or metastatic cancer. All spines were x-rayed before testing to preclude significant spinal disease or preexisting fractures. In 4 cadavers, the top of the skull and the brain were removed and the remaining skull and spine to the bottom of T-3 were isolated. In 5 isolated specimens, the head was intact. In 1 isolated specimen, the head was removed, leaving the spine from C-1 to T-3. Ligaments in the isolated columns were left intact by careful dissection. Four intact cadaver torsos were also studied. All specimens were kept at 2°C until studied and were moistened with lactated Ringer's solution both before and during testing.

The isolated columns were fixed at the base in iron rings, blocked with methyl methacrylate reinforced with wire, and clamped to the piston frame. In the specimens with partial skulls, the inferior end of the force piston was blocked into the base of the skull, which was filled with methyl methacrylate. In the headless column, the machine piston was blocked into methyl methacrylate at C-1. The intact torsos were supported under the arms with rigid yokes and were fixed

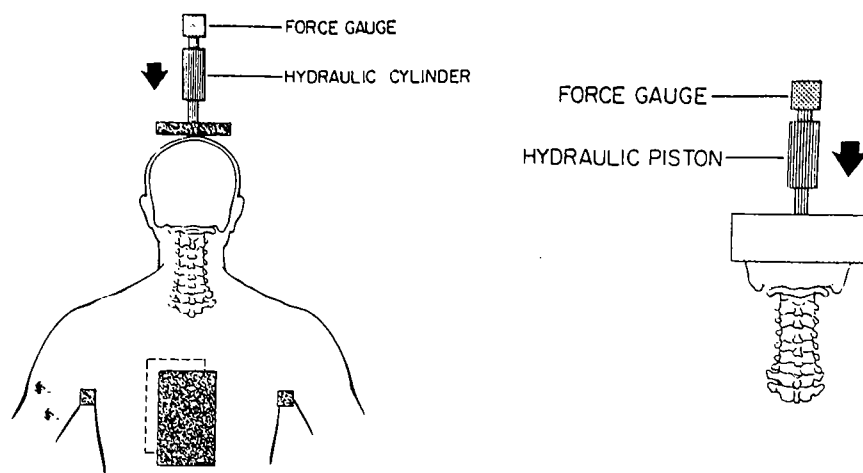


FIG. 1. Diagrammatic representation of load delivery. *Left*, intact specimen; *right*, isolated column.

anteriorly and posteriorly with 30- × 30-cm compression plates.

Dynamic loads were applied to the spinal columns with a Series 810 Materials Testing System (MTS) (MTS Systems Corp., Minneapolis, Minnesota) at constant rates of 23 to 152 cm/second. In one slow rate study (S18), the load was applied with an Instron device (Instron Corp., Canton, Massachusetts) at 0.25 cm/second. A vertical 10-cm piston stroke was used for all studies. The isolated columns with heads and the intact cadavers were compressed with a 10- × 10-cm steel plate. In the remaining specimens, the piston of the MTS device was seated in methyl methacrylate (Fig. 1).

Preparations S12, S15, S18, and S21 were preflexed with respect to the horizontal at 25° of the Frankfurt plane of the head. Specimens S14 and S43 were preextended 25° with respect to the horizontal. All preparations were mounted vertically, and all heads and necks were unrestrained, but initially positioned as shown in Table 1.

After each test, the specimens were studied with roentgenography and carefully dissected by at least one neurosurgeon. Specimen failure was considered to be the point where the force decreased markedly, which occurred at bone, disc, or ligament disruption. The energy for specimen failure was calculated from the force, and displacement up to the maximal machine displacement and the machine force were recorded at failure. A Honeywell Model 1858 Visicorder (Honeywell, Inc., Chicago, Illinois) was used to record the force and machine displacement. Films were taken with a Hycam camera (Red Lakes Corp., Campbell, California) at 1000 frames/second.

RESULTS

The findings are summarized in Table 1. The average failure load with axially applied loads was 3567 N with a mean piston displacement of 4.7 cm and an average energy of 168 J (Table 2). For the four preflexed specimens, an average load of 1823 N was observed with a mean piston displacement of 1.5 cm and an average energy of 27 J. The preextended specimens failed at a mean load of 1089 N, an average piston displacement of 3 cm, and an average energy of 33 J.

Table 3 gives a comparison of failure modes and the mean load, mean piston displacement, and energies for the various specimens. In general, the specimens failed with preflexion or in the flexion mode at substantially lower forces (approximately 50%) than with the axially applied loads or in the two specimens that failed in direct axial compression. The preex-

tended specimens failed at the lowest force levels at an angle of 80 to 100°. Both posterior and anterior disc bulging was observed with flexion. In the three extension injuries, the anterior longitudinal ligaments and disc anulus fibers were avulsed; no posterior longitudinal ligament or posterior element abnormality was observed. Three cases of atlantoaxial dislocation were observed: two in flexion (Fig. 2) and one in extension. Disruption of the anterior longitudinal ligament was observed in one specimen compressed with an axial load.

A substantial number of posterior ligamentous disruptions were observed in the flexion mode without vertebral body fractures. The largest failure force was observed in the shortest preparation that failed in the axial mode (S20). A tendency for the preparations to fail at lower force levels with more slowly applied loads was observed.

The high speed films demonstrated routine forward rotation of the head with force application in the region of the vertex allowing the force plate to slip posteriorly. This occurred with the axial loads applied to Preparations S16, S19 (Fig. 3), and S27. The preflexed loaded specimens continued to flex forward until injury occurred (Fig. 4). Similarly, the specimens in preextension continued to rotate rearward until injury was produced (Fig. 5). No failures were observed at the fixation points.

DISCUSSION

The majority of experimental studies performed by others have utilized motion (functional) segments consisting of two vertebral bodies with interposed disc and ligaments. Using motion segments, Panjabi et al. performed selective ablations to measure the strength of the remaining structures with angular and axial loads. They found that components of both anterior and posterior compartments were necessary for spinal stability and that ligamentous failure occurred suddenly without considerable prior attenuation (13).

Roaf conducted studies in unembalmed functional spinal units from the cervical spine with various injury forces (14). He concluded that, in flexion, compression fracture of the vertebral body always precedes posterior ligament injury, suggesting a fulcrum in the vertebral body. He was unable to produce ligamentous or disc injury in the absence of fracture either in flexion or in extension. Allen et al., in a retrospective review, saw posterior ligament disruption associated with only the most severe vertebral body fractures (1). However, the posterior ligaments were altered in most of our specimens injured in flexion (Figs. 2, 4, and 6).

TABLE 1
Results of Studies

Specimen No./Preparation	Area Applied	Age	Load (N) ^a	Load Rate (cm/s)	Piston Displacement (cm) ^b	Machine Energy (J) ^c	Failure Mode	Anatomic Changes ^d
<i>Axial loading</i>								
S6 Base of skull to T-3	Vertex	67	4500	120	3.66	82	Axial	C-5 burst fracture; compression fracture of posterior elements and disruption of posterior ligaments
S10 Base of skull to T-3	2 cm posterior to the vertex	76	4410	130	7.4	160	Extension	Fracture of the body of C-2 and through the base of the odontoid process, with disruption of the anterior longitudinal ligament and the anulus (Fig. 5)
S13 Head to T-3	1 cm anterior to the vertex	84	2309	112	3.71	42	Flexion	Compression fracture of the arches of C-2 and C-3; disruption of the posterior ligaments
S19 Base of skull to T-3	Vertex	61	1509	23	1.14	8	Flexion	Teardrop and arch fractures of C-2 (Fig. 3)
S20 C-1 to T-3	Vertex	64	7439	82	1.00	36	Axial	Disruption of the anterior longitudinal ligaments at C-6, C-7; left facet fractures of C-3, C-4, and C-5
S16 Whole torso	Vertex	80	2936	112	9.20	135	Flexion	Disruption of the posterior ligaments at C-1, C-2; plate slipped to the occiput
S17 Whole torso	Vertex	65	1868	142	7.2	67	Flexion	Disruption of the posterior ligaments at C-1, C-2; plate slipped to the occiput

Table 1 continues on next page.

^a Maximal load at failure. One Newton (N) = 0.2248 lb.^b Displacement at maximal failure load.^c Energy at failure. One Joule (J) = 0.737 ft-lb.^d Posterior ligaments include the interspinous ligaments, ligamentum nuchae, ligamentum flavum, and others posterior to the posterior longitudinal ligament.TABLE 2
Comparison of Force Directions

	Mean Age	Mean Load (N)	SEM ^a	Mean Piston Displacement (cm)	Mean Failure Energy (J)
Axial	71	3567	722	4.7	168
Preflexion	46	1823	416	1.5	27
Preextension	64	1089	299	3.0	33

^a Standard error of the mean = $SD/\sqrt{n-1}$.

Bauze and Adrian suggested that studies using isolated segments are not physiological because they ignore the changing axis and multiple forces on the larger spinal columns (3). They used spinal columns that included the upper thoracic spine, but placed rigid pins in the spinal canal to C-5, eliminating motion of the lower cervical and upper thoracic spine. The demonstrated fracture-dislocations at C-5 may have reflected the high stresses at the fixation point.

Selecki and Williams conducted compression studies in

TABLE 3
Comparison of Failure Modes

	Mean Load (N)	SEM ^a	Mean Piston Displacement (cm)	Mean Failure Energy (J)
Axial	5969	1049	2.3	137
Flexion	1989	253	3.4	68
Extension	2196	926	4.5	99

^a Standard error of the mean = $SD/\sqrt{n-1}$.

frozen, unembalmed cadavers, which were refrozen between trials. They measured the pressure between samples, including the T-1 vertebra and the distal end of the atlantooccipital articulation membrane, foramen magnum, and base of the skull (17). Hyperextension, flexion, rotation, and combinations of these, delivered at slow rates, were applied to 22 human specimens. Injuries secondary to extension were most commonly seen in the lower cervical spine. Only 2 of 7 of the hyperextended preparations had arch or joint fractures, although all demonstrated rupture of the anterior longitudinal ligament and disc at angles of 80 to 90°. In axial compression,

TABLE 1—continued

Specimen No./Preparation	Area Applied	Age	Load (N) ^a	Load Rate (cm/s)	Piston Displacement (cm) ^b	Machine Energy (J) ^c	Failure Mode	Anatomic Changes ^d
<i>Preflexion loads (25°)</i>								
S12 Head to T-2	Inion	57	1779	152	0.64	6	Flexion	Atlantoaxial dislocation; disruption of the posterior ligamentous complex at C-1, C-2 (Fig. 2)
S15 Head to T-3 **	2.5 cm anterior to the vertex	54	3000	122	2.5	75	Flexion	Fracture of the inferior anterior body of C-4 and the supporting anterior body of C-5 with complete dislocation; posterior ligament disruption (Fig. 6)
S18 Head to T-3	1.0 cm anterior to the vertex	41	645	0.25	0.48	2	Flexion	Atlantoaxial dislocation; disruption of the transverse atlantal ligament; posterior ligaments stretched at C-1, C-2; capsules disrupted on the left
S21 Base of skull to T-3	2.0 cm anterior to the vertex	30	1868	25	2.33	20	Flexion	Fractures of C-4 and C-5 with angulation; partial disruption of the posterior ligaments (Fig. 4)
<i>Preextension loads (25°)</i>								
S14 Whole torso **	Hairline	71	1512	122	3.61	26	Extension	Avulsion fracture of C-4 and disruption of the anterior longitudinal ligament and anulus of C-5, C-6
S43 Head to T-3	Hairline	56	667.2	40	2.5	8	Extension	Atlantoaxial dislocation and disruption of the anterior longitudinal ligament and anulus at C-2 and C-5; disruption of the transverse atlantal ligament

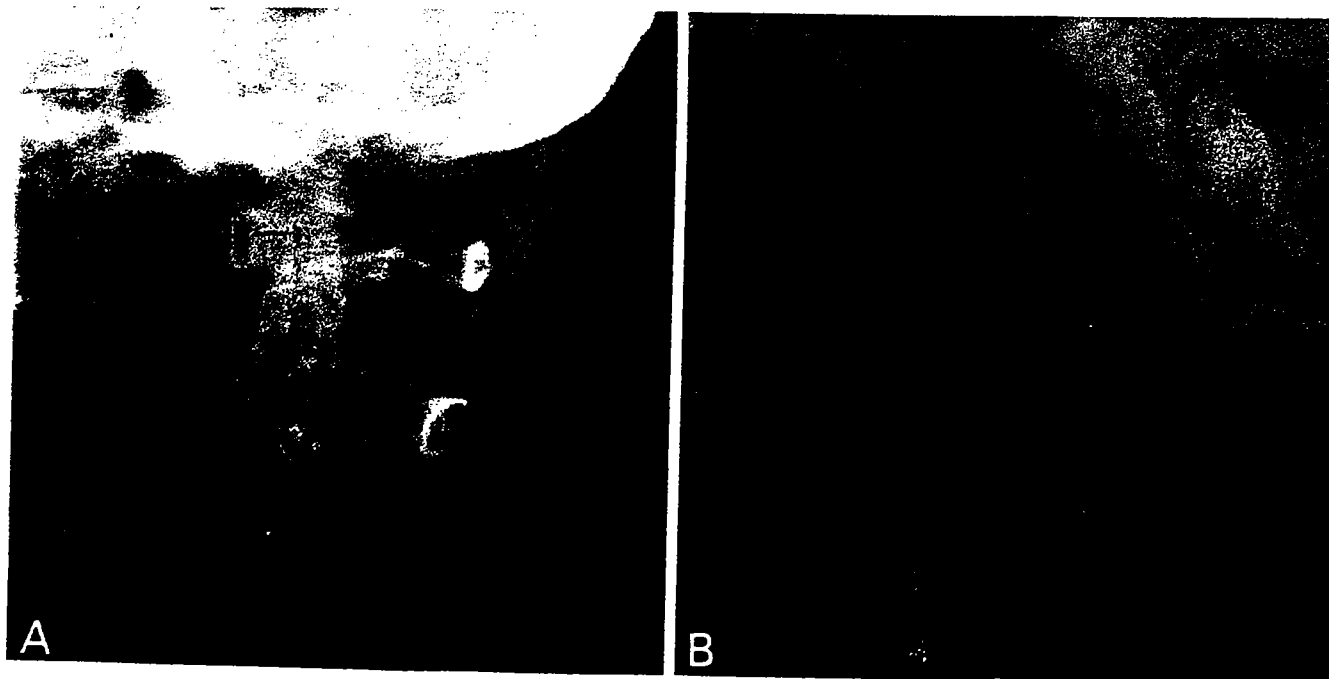


FIG. 2. Specimen S12: Preflexion load. Flexion (A) and extension (B) views show atlantoaxial dislocation. The line defines the atlanto-dens interval. A complete disruption of the posterior ligaments at C-1, C-2 was seen.

disc trauma was followed by fractures of the vertebral bodies and articulations with disruptions of the anterior and posterior longitudinal ligaments; these were probably caused by forces produced by disc protrusion. Similar injuries at proportional loads were seen in the present investigation. Spinal dislocation routinely occurred at C-3, C-4 and C-4, C-5. In 3 flexion specimens, disruption of the posterior ligamentous complex and fanning of the elements were evident early, in conjunction with posterior disc protrusions. With further increases in load, teardrop and wedge fractures of the vertebral bodies were seen. Selecki and Williams noted that flexion injuries were more extensive and were produced at lower pressures than those observed with axial loads.

In contrast, Roaf was unable to disrupt the anterior longitudinal ligament with pure extension because compression fractures of the posterior elements occurred first (14). King et al. suggested that the facets absorb much of the compression load and tension, decreasing the likelihood of vertebral body and posterior arch injury (8). In the three extension injuries in this study, anterior longitudinal ligament and anulus avulsions occurred without disruption of the posterior elements or ligaments (Fig. 5). The importance of this finding is obvious, because many consider extension injuries to be relatively stable, presumably suggesting that ligamentous injury has not occurred (20). Furthermore, the substantial number of posterior ligament injuries without vertebral body fractures in our series suggests that the intact column distributes the forces differently than functional elements.

The forces required to produce failure in axial compression were greater in our series than those required for flexion or extension. These findings are similar to those predicted on the basis of mathematical models or seen in experimental studies that have demonstrated that the preflexed or preextended column is weaker than the axially loaded column (15-17). Mathematical studies also predict proportionately higher strengths of shorter columns than longer ones (20), a finding seen in these investigations.

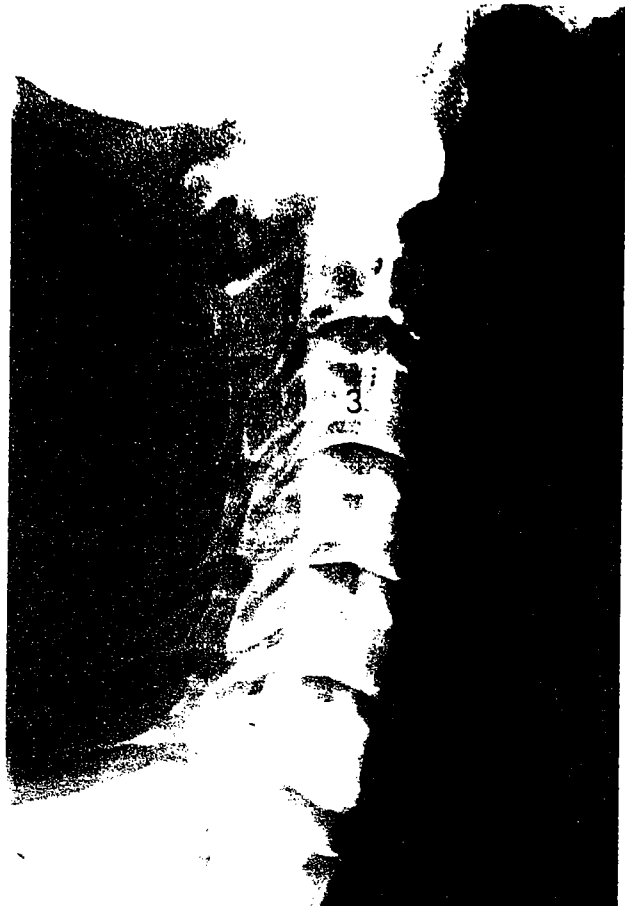


FIG. 3. Specimen S19: Axial compression. Teardrop fracture of C-2 (arrowhead). A fracture of the arch of C-2 was found.

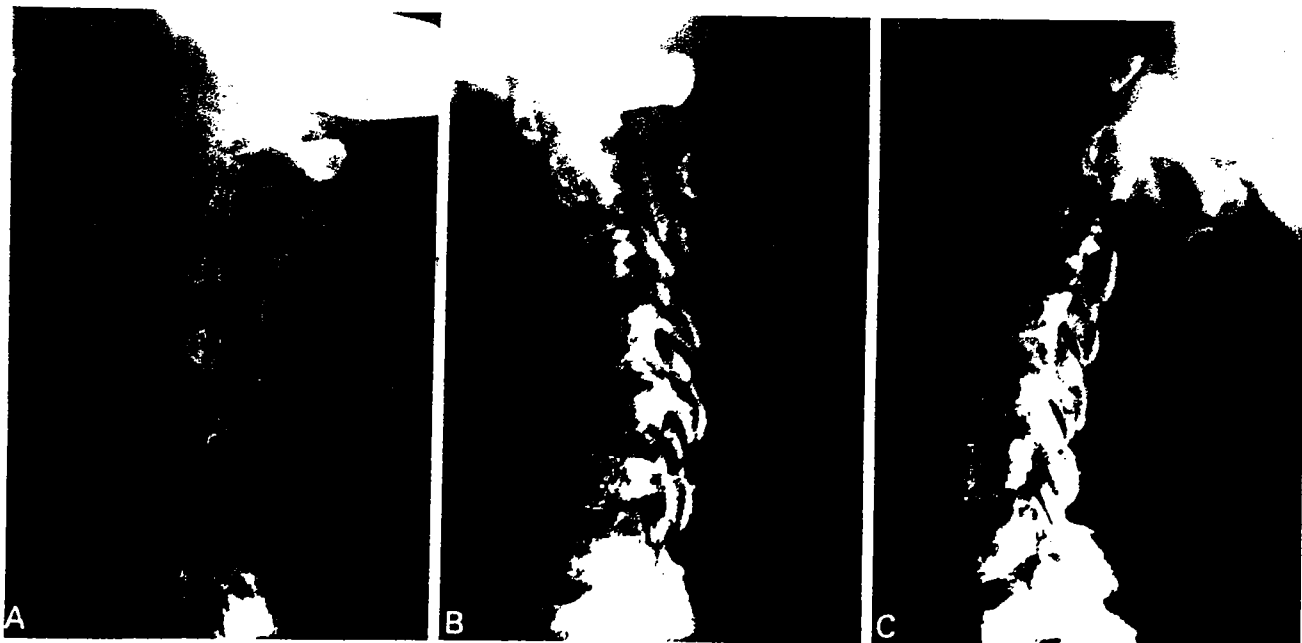


FIG. 4. Specimen S21: Preflexion load. Fractures of the bodies of C-4 and C-5. Neutral (A), flexion (B), and extension (C) views demonstrate movement into the vertebral spinal canal; minimal fanning of the spinous processes was evident, although there was partial avulsion and attenuation of the posterior ligaments.

Hodgson and Thomas applied static and dynamic loads to the heads of intact embalmed cadavers. They found that both the level of cervical spine injury and failures were related to the degree of restriction of motion at the atlantooccipital junction as well as to head impact location (6). Similarly, Nusholtz et al. conducted studies on 12 unembalmed cadavers (11). They used a horizontal piston to strike the skull vertex of fixed cadavers, allowing motion of the head. Three-dimensional cinematography recorded spine and head movements. Injuries to the cervical spine occurred in 11 of their 12 specimens with forces ranging from 1,800 to 11,000 N and energies of 3 to 248 J. They emphasized that, because of the complexity of spine motion and directional injury patterns, absolute injury levels for specific types of trauma are difficult to predict except at upper spine levels. The findings of Nusholtz et al. are in the range observed in our study.

Three cases of atlantoaxial dislocation were seen in our investigation. In two, the primary force was flexion at relatively low loads (Fig. 2). The third case was produced in extension. In one of the flexion and in the extension specimen, there was disruption of the transverse atlantal ligament; in the extension study, there was also disruption of the anterior longitudinal ligament. The mechanism of atlantoaxial dislocation has classically been said to be flexion with disruption of a weakened transverse atlantal ligament across the odontoid process; an additional component of longitudinal shear may also be important (10, 16). It seems that this phenomenon



FIG. 5. Specimen S10: Preextension load. Fracture of C-2 (black arrowhead—note similarity to Fig. 3) and fracture through the base of the odontoid process (white arrow), with disruption of the anterior longitudinal ligament.



FIG. 6. Specimen S15: Preflexion load. Dislocation at C-4, C-5.

may also occur in extension, although the specific mechanism cannot be hypothesized on the basis of one trial. In Preparation S10, a fracture at the base of the odontoid process was observed with disruption of the anterior longitudinal ligament (Fig. 5); in this preparation, the transverse atlantal ligament was intact.

Although no definite age comparisons could be made in this investigation, it seemed that failure loads were lower in older specimens. The mechanical strengths of human vertebrae have been shown to be greatest between 20 to 39 years of age and to begin to decrease after age 40. Between 40 and 49 years of age, the tensile strength is approximately 80% that of the younger group; the compressive properties between ages 60 and 79 are 54% and the torsional values are 71% of the younger values (21). For the intervertebral disc, the greatest strengths are also seen between 20 and 39 years of age, and between 40 to 49 years of age the tensile properties are reduced to 78% and the torsional properties are reduced to 85%.

Tkaczuk has demonstrated that human anterior and posterior longitudinal ligaments of the lumbar spinal column demonstrate a progressive decrease in elongation and residual deformation immediately after birth and after 20 to 30 years of age progress more slowly. By the 6th decade, the values are approximately 80% of those at 20 years (18). Consequently, absolute forces measured should be weighted according to the ages of the specimens.

Studies of the influence of postmortem storage on the tensile strength of tissues suggest that, within 96 hours of death, the greatest cause of change in properties is dehydration (19). Because of the experimental methods, these factors probably were not significant in the present study. The effect of muscle tone on failure loads is also difficult to assess. It has been suggested that it plays a small role in compression (20).

Our findings emphasize the variety of spinal injuries produced by specific force vectors. It is clear that spinal ligaments can be easily disrupted in flexion or extension, which may manifest itself only as cervical soft tissue trauma not easily identified radiographically. The difficulty in retrospectively assigning forces to given lesions is evident, as are the hazards of determining therapy based on conventional wisdom. The prominence of ligamentous injuries, especially of the anterior longitudinal ligament, produced by three different force vectors addresses the requirement of prudently evaluating each patient before the assumption of spinal stability.

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COMMENT

The authors present an interesting biomechanical study of human cadaver cervical spinal columns subjected to vertical, forward, or rearward compression forces. The data indicate that the interpretation of the force mechanisms resulting in specific radiographic abnormalities may be difficult. Moreover, radiographic studies of human cervical spine injuries should be viewed with caution when attempting to predict the degree and severity of ligamentous injury, i.e., posttraumatic spinal stability. The authors also give an excellent discussion of prior biomechanical studies of various human cadaver cervical spinal column preparations.

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