

MECHANISMS OF HYPERFLEXION CERVICAL SPINE INJURY

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ABSTRACT

Hyperflexion injuries of the human cervical spine commonly occur in vehicular crashes, contact sports, diving, and falls. Flexion related injuries constitute a high percentage of all cervical spine injuries. The objective of this study was to determine the mechanisms and tolerance of the human cervical spine under hyperflexion loading conditions through *in vitro* biomechanical experimentation. The impact load was delivered by an electrohydraulic piston to the cranium of a cadaver head-neck complex in a preflexed configuration. Measured biomechanical quantities included head impact forces, neck forces and moments, kinematics, spinal cord pressures, and pre-test alignment parameters. A total of thirteen specimens were tested. Minor injuries included mainly disruption of the lower cervical spine posterior ligament complex at one level. Major injuries included extensive ligamentous injury usually with vertebral fractures and/or complete dislocations. The anterior eccentricity of the occipital condyle with respect to T1 body was the most critical variable which influenced the loading condition and injury outcome. The spinal cord pressures were consistent with the severity of joint disruption and load magnitude. The average moment magnitudes for minor injuries were 52 Nm, and 97 Nm for specimens with major trauma. Using logistic regression techniques, the 25 % probability of major neck injury was determined to occur at 1850 N of axial neck force and 62 Nm of injury bending moment.

HUMAN CERVICAL SPINE hyperflexion injuries commonly occur in vehicular crashes, contact sports, and falls. Hyperflexion of the cervical spine is a forced forward bending exceeding the normal physiological range. The resulting trauma may include those classified in the literature as hyperflexion, flexion, compressive flexion, and distractive flexion injuries (Allen *et al.*, 1982; Yoganandan *et al.*, 1990; Harris and Mirvis 1996). Epidemiological studies have indicated that the flexion mechanism is the most common cause of neck trauma and accounts for 48-70% of all cervical spine injuries (Allen *et al.*, 1982; Yoganandan *et al.*, 1990).

Hyperflexion injuries are often associated with localized ligamentous disruption of the cervical spine (Harris and Mirvis 1996). They may be characterized by localized kyphotic angulation at the level of injury, anterior dislocation or rotation of the subluxed vertebra, anterior narrowing and posterior widening of the disc space, dislocation of the articulating facets, or widening of the space between spinous processes ("fanning") (Green *et al.*, 1981; Harris and Mirvis 1996). In the absence of dislocation, flexion injuries are difficult to detect by radiographic means since there are often no bony fractures. The injured cervical spine may appear normal in radiographic films when the spine is in neutral or extended positions. The radiographic signs of injury are only evident in flexion. Such injuries may lead to late dislocation or late instability of the vertebral column with potentially disastrous consequences (Green *et al.*, 1981). These injuries are difficult to stabilize with non-operative treatment (Savini *et al.*, 1987).

Results from our previous experimental studies have demonstrated that the pre-alignment condition of the head-neck complex significantly influences the injury mechanism and biomechanical response variables (Pintar *et al.*, 1990a; Pintar *et al.*, 1995a; Pintar *et al.*, 1995b). Determining the correlation between the alignment condition, biomechanical responses, and injury mechanism may assist in the evaluation of injury risks and preventive measures. The present *in vitro* experimental study was designed to biomechanically determine the mechanism of injury and human tolerance for hyperflexion injury of the cervical spine with head impact.

METHODS

The dynamic experiments were performed on thirteen human cadaver head-neck complexes using similar techniques according to a previously established protocol (Pintar *et al.*, 1990a). Briefly, the fresh head-neck complexes were isolated from the human cadaver at the T2-T3 disc. Medical records and radiographs were examined to exclude specimens with pre-existing trauma or bone disease. The posterior muscles and skin were kept intact while those on the lateral and anterior sides were dissected. The inferior end of the specimen, along with the skin, was fixed with polymethyl-methacrylate (PMMA) while leaving the C7-T1 joint and above unrestrained. Retroreflective pin targets were placed in the anterior vertebral body, the lateral vertebral masses, and the cranium. The spinal cord pressures during loading were recorded by seven pressure sensors attached to an instrumented artificial spinal cord developed previously (Pintar *et al.*, 1996).

The inferior mount of the preparation was then bolted to a six-axis load cell and firmly attached to an x-y cross table of the custom-designed servo-controlled electrohydraulic piston. The specimen was flexed prior to loading so that the head impact would produce a hyperflexion of the cervical spine (Figure 1). A lateral radiograph was taken prior to the impact to record the geometric relations of the head, vertebrae, targets, and the impactor. A flat plate with ensolite padding attached to the piston of the testing device served as the impact surface. A vertical impact load was delivered to the head at 2 to 5 m/sec by the electrohydraulic piston.

Transducer measurements included an in-series load cell and displacement gauge in the piston. A six-axis load cell recorded the generalized force histories at the

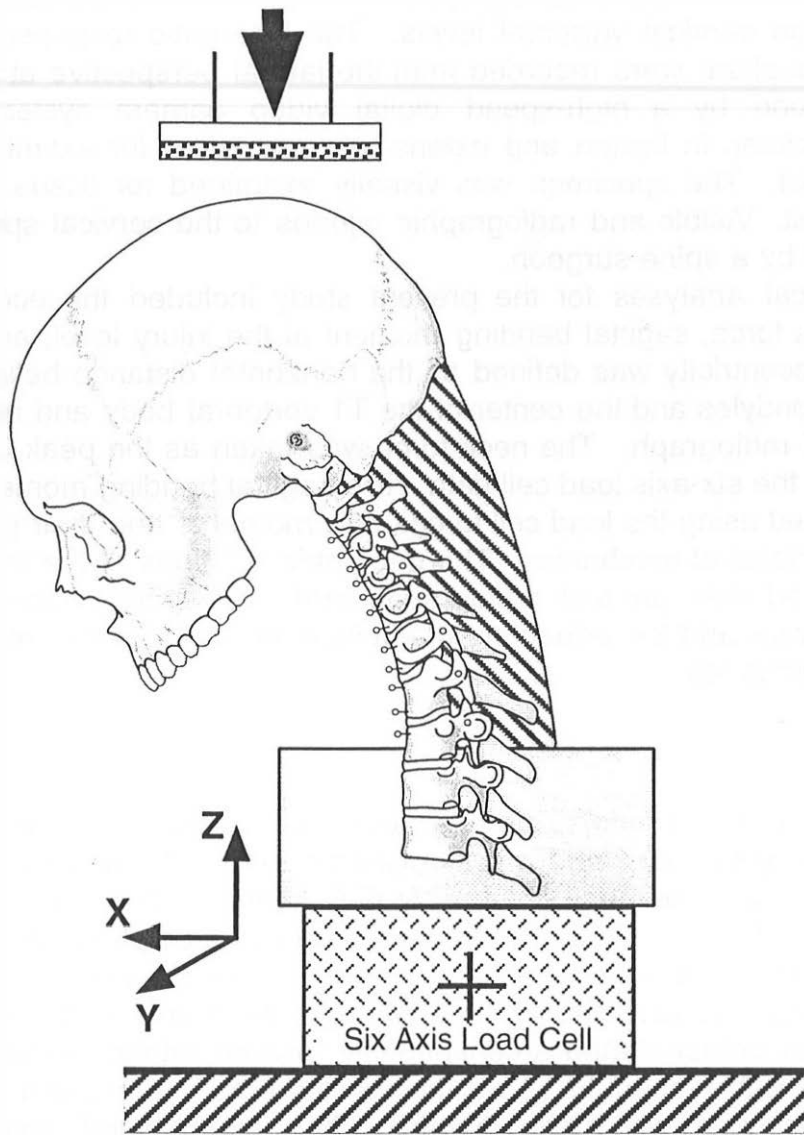


Figure 1: Schematic of the experimental test setup

inferior end of the preparation. The transient spinal cord pressures were recorded by the sensors at the seven cervical vertebral levels. The kinematic responses of the head-neck in the sagittal plane were recorded from the lateral perspective at a rate of 4500 frames per second by a high-speed digital video camera system. The radiographs of the specimen in flexion and extension were taken for examination of the injuries after the test. The specimen was visually examined for tissue damage immediately after the test. Visible and radiographic injuries to the cervical spine were identified and classified by a spine surgeon.

The biomechanical analyses for the present study included the eccentricity, head impact force, neck force, sagittal bending moment at the injury level, and spinal cord pressures. The eccentricity was defined as the horizontal distance between the center of the occipital condyles and the center of the T1 vertebral body and measured from the pre-test lateral radiograph. The neck force was taken as the peak of the z-axis load (vertical) from the six-axis load cell data. The sagittal bending moment at the site of injury was obtained using the load cell forces and moments and their geometric relations based on principles of mechanics. The geometric relations of the forces and moments were measured from pre-test radiographs and high-speed video images. Using a free-body diagram and the equations of equilibrium, the bending moment at the injured level was calculated.

RESULTS

The hyperflexion injuries produced in this study were classified as either minor or major injuries. Minor injuries included mainly disruption of the lower cervical spine posterior ligament complex at one level. Major injuries included extensive ligamentous injury usually with vertebral fractures and/or complete dislocations (Figure 2). The two injury groups exhibited different cervical spine deformation patterns in the sagittal plane as revealed by the analysis of the high-speed video. The group with minor injuries demonstrated a continuously forward rotational deformation of the cervical vertebrae with respect to T1 resulting in extreme hyperflexion of one of the lower joints. Specimens with major injuries often experienced some initial compression of the entire column followed by local hyperflexion at the injured level.

The resulting injuries depended on the initial specimen alignment condition which was measured in terms of eccentricity. The eccentricities of all the tests ranged from 2.0 to 10.2 cm (Table 1). The minor injury group had an average eccentricity of 7.6 cm, and the group with major injuries was associated with smaller eccentricities (mean = 3.1 cm).

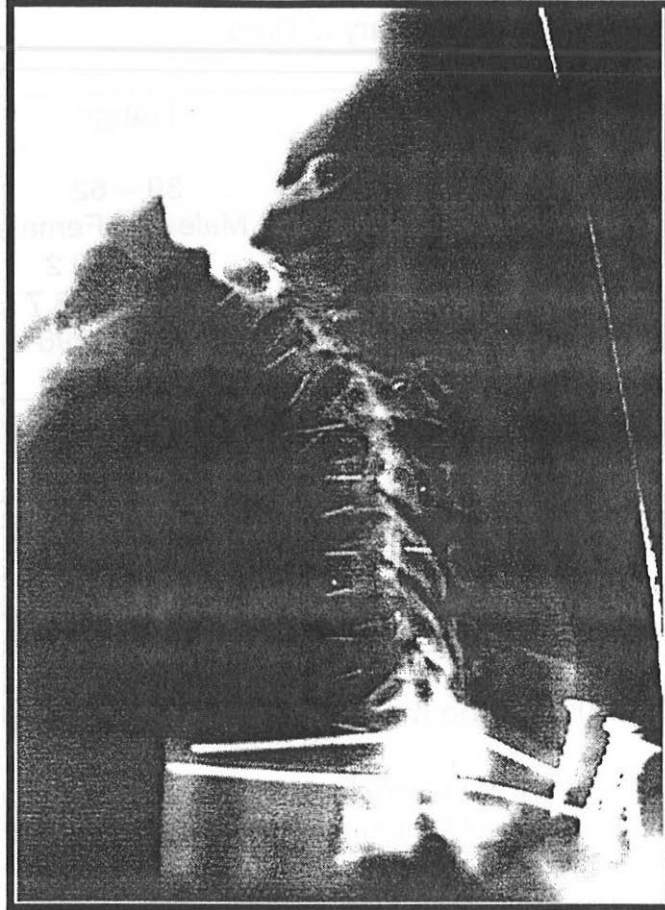


Figure 2: Post-test radiograph of specimen with major injury. Note the wedge tear-drop fracture of C4 with distraction of the posterior ligaments at C4-C5.

TABLE 1: Summary of Data

<u>Parameter</u>	<u>Mean</u>	<u>Range</u>
Specimen age (yrs)	59	39 – 82
Specimen gender		9 Males / 4 Females
Alignment eccentricity (cm)	5.2	2.0 – 10.2
Moment at injury level (Nm)	76.1	19.4 – 168.7
Axial neck force peak (N)	2283	634 – 4298
Axial head force peak (N)	5400	3000 – 9700

The injury outcome was directly related to the load magnitude and load component (axial force and bending moment) in the cervical spine. The peak axial head impact force ranged from 3000 to 9700 N. The peak axial (z-direction) neck force ranged from 634 to 4298 N. The peak flexion bending moment at the injured level ranged from 19 to 169 Nm. The minor injury group sustained significantly lower ($p < 0.02$, ANOVA, factorial) magnitudes of axial neck force (mean = 1442 N) and moment at injury (mean = 52 Nm) than the major injury group (force mean = 3004 N; moment mean = 97 Nm).

The spinal cord pressures were consistent with the biomechanical parameters and the severity of injury. The pressures at uninjured levels were of low or zero magnitude while it was generally higher at the level of injury. The cord pressures at or near the level of injury were generally below 20 N/cm² for the minor injury group. Much higher magnitudes of cord pressures (45 to 100 N/cm²) were recorded at or near injured levels for the group with major injuries.

Additional statistical analysis was done to determine the probability of major injury with respect to moment and force. Logistic regression curves were generated for probability of major injury with respect to neck axial force and injury bending moment (Figure 3). The 25 % probability of major neck injury for axial neck load was determined at 1850 N ($p < 0.0024$ and for injury bending moment at 62 Nm ($p < 0.0009$).

DISCUSSION

The present study is an extension of our earlier research which focused on the biodynamics of compression injuries of the human cervical spine (Yoganandan *et al.*, 1986; Pintar *et al.*, 1990a; Pintar *et al.*, 1990b; Yoganandan *et al.*, 1991; Pintar *et al.*, 1995a; Pintar *et al.*, 1995b; Pintar *et al.*, 1996). Although the methodology used is similar to that of the previous studies, the loading vector to the cervical spine in this study was chosen to induce primarily a flexion bending moment rather than an axial compressive force. The number of specimens tested was determined based upon the analysis of the resulting output parameters. Initially ten specimens were completed with subsequent tests added to the ensemble until significance in the data parameters

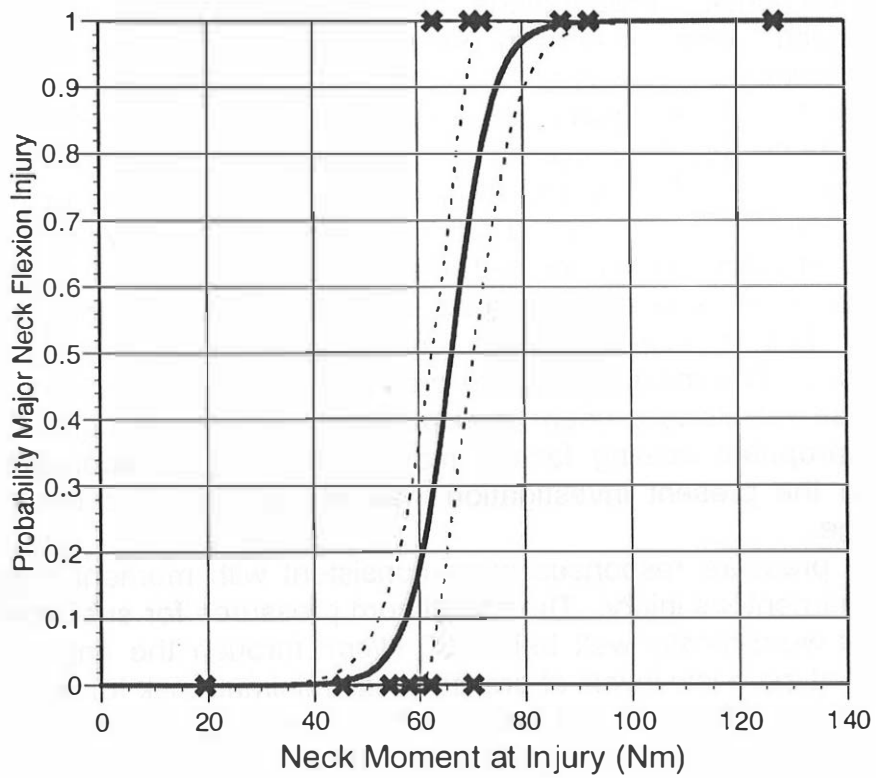
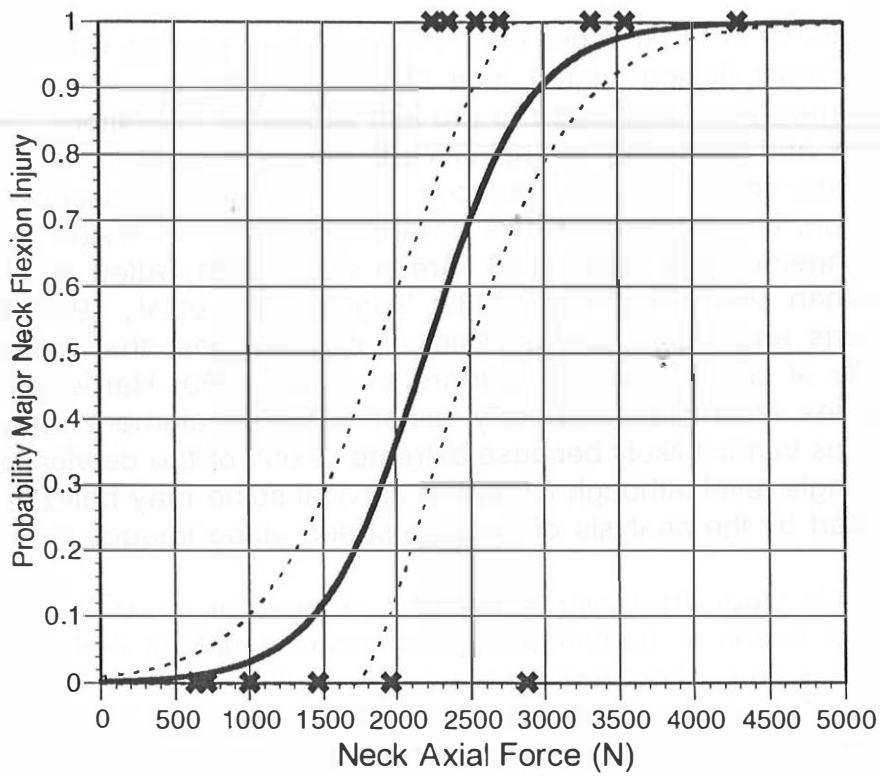


Figure 3: Logistic regression curves for probability of major neck injury versus peak neck axial force (top plot) and neck bending moment at injury level (bottom plot). The dotted lines indicate one standard deviation.

was reached and a balance in the number of major and minor injuries was produced. The resulting injuries were flexion-related joint disruption with or without vertebral fractures. Injury outcomes were correlated to pre-test alignment conditions, vertebral kinematics, neck forces and moments, and spinal cord pressures.

The injuries produced in this study are consistent with those described in the literature on hyperflexion, flexion, compressive flexion, or distractive flexion injuries of the cervical spine (Schneider and Kahn 1956; Green *et al.*, 1981; Allen *et al.*, 1982; Braakman and Braakman 1987; Kim *et al.*, 1989; Yoganandan *et al.*, 1990; Barquet and Dubra 1993; Harris and Mirvis 1996). Clinical data suggest that hyperflexion injuries occur primarily at single levels (Yoganandan *et al.*, 1990; Harris and Mirvis 1996). Adjacent injuries tend to be relatively minor posterior element fractures or ligament avulsions. This is most likely because extreme flexion of the cervical spine is highly localized at a single level although the entire cervical spine may bend in flexion in general, as confirmed by the analysis of the high-speed video images taken in the present investigation.

The results of this study demonstrate that the pre-test alignment condition, in terms of the eccentricity, is one of the critical biomechanical variables that determines injury outcome. Greater values of eccentricity tended to result in lower neck forces and relatively minor ligamentous hyperflexion injuries. The preparations that sustained minor injuries had significantly greater eccentricities and significantly lower neck loads and injury bending moments. Preparations that sustained major injuries were generally associated with lower eccentricity values, but greater neck forces and bending moments. A number of specimens in this group also sustained vertebral fractures. This injury was consistent with initial compression in the location of fracture, followed by local extreme flexion at the injured level as confirmed from the high-speed video images. The neck load also tended to peak before the bending moment. It therefore follows that neck injuries associated with vertebral fracture may be correlated more to the axial force and bending injuries with primarily ligamentous disruption may be more correlated to bending moment. Other variables including the specimen quality and age are factors that could be considered to affect the resulting biomechanical responses. The mean age of the present ensemble was 59 years and therefore to apply these results to a younger population which is at higher risk for major neck injury, appropriate scaling factors may have to be incorporated. The number of samples in the present investigation was not adequate to determine a quantitative effect of age.

The spinal cord pressure responses were consistent with moment magnitude and severity of osteoligamentous injury. The spinal cord pressures for specimens with relatively low moments were mostly well below 20 N/cm² through the entire cervical spine. The spinal cord at such low levels of pressure has minimum risk for acute injury (Pintar *et al.*, 1996). This agrees with the literature that neurologic damage in minor hyperflexion injury is usually mild and reversible (Allen *et al.*, 1982; Braakman and Braakman 1987). The cord pressures for specimens with higher forces and bending moments had much higher spinal cord pressures at or near the injured level indicating increased risk of cord injury. In particular, one specimen had a tear-drop fracture with tremendous spinal deformations and recorded the highest cord pressure (100 N/cm²). This result agrees with the clinical observation that flexion tear-drop fractures may be

characterized by acute anterior cervical cord syndrome with immediate complete quadriplegia (Allen *et al.*, 1982; Kim *et al.*, 1989).

A severe flexion-related injury commonly associated with complete quadriplegia is the bilateral locked facet dislocation. This injury is seen in patients involved in vehicular collisions, football, hockey, and diving activities. It occurs commonly without vertebral fracture and involves a complete disruption of the intervertebral joint at one level of the lower cervical spine. These injuries have been commonly associated with a flexion-distraction loading vector (Allen *et al.*, 1982; Kazarian 1982) but more recently with a flexion-compression loading vector (Myers and Winkelstein 1995). It is interesting to note that in the present series of flexion-related tests, complete dislocations were produced at one level without bony fracture, but never with a "locking" of the facet joints. This was most likely due to the absence of muscle tone in the cadaver model since the locking of the facet is maintained by contraction of neck musculature in the surviving patient. In fact, the treatment of patients with bilateral locked facets begins with traction of the neck to release the locking and return the spine to its normal alignment before fixation procedures are done to restabilize the spine. The understanding of what can be produced in a laboratory setting and what is seen in the clinical setting leads to a new possible explanation of the mechanism of bilateral locked facets (Figure 4). This injury can be produced in either flexion-distraction or flexion-compression as long as the force vector to the head places the spine in a predominantly bending mode. First, the bending of the spine produces tearing in the posterior ligaments of one of the lower levels of the cervical spine mainly because the bending moments are highest in this region. Then as hyperflexion of the spine produces total disruption of the joint the reactionary response of the extensor and flexor muscles to stabilize the spine occurs and pulls down on the upper portion of the cervical spine. The downward contraction of the muscles at the time of hyperflexion of the spine slides the upper portion of the dislocated spine forward and down causing the superior facet to lock in front of the inferior facet. This locking action pinches the spinal cord often causing neurologic trauma. It is known that the timing of muscular contraction after an event can not occur faster than approximately 100 to 150 msec. This timing as confirmed by the high speed video recordings in the present series of tests occurs approximately when the spine is in its maximum bending mode. This plausible mechanism of locked facets explains its occurrence under many different flexion related loading vectors.

Both the sagittal bending moment at the injured level and the neck load were found to be consistent biomechanical variables which quantified the severity of hyperflexion injuries. A flexion moment in the cervical spine induces tension in the posterior ligament complex and compression in the anterior portion of the vertebral bodies and discs. Injury of ligaments are caused by tensile loading while vertebral body fractures are usually caused by compressive loading. Thus, a high flexion moment with low axial compressive force may cause tensile failure of the posterior ligamentous tissues and progressive bending with increasing moment magnitude. A simple ligamentous injury therefore, might be quantified by the bending moment alone. Most of the specimens with minor injuries in the present study fall into this category. The average bending moment for these specimens was 52 Nm. The average bending moment for the more severe trauma based upon the remaining

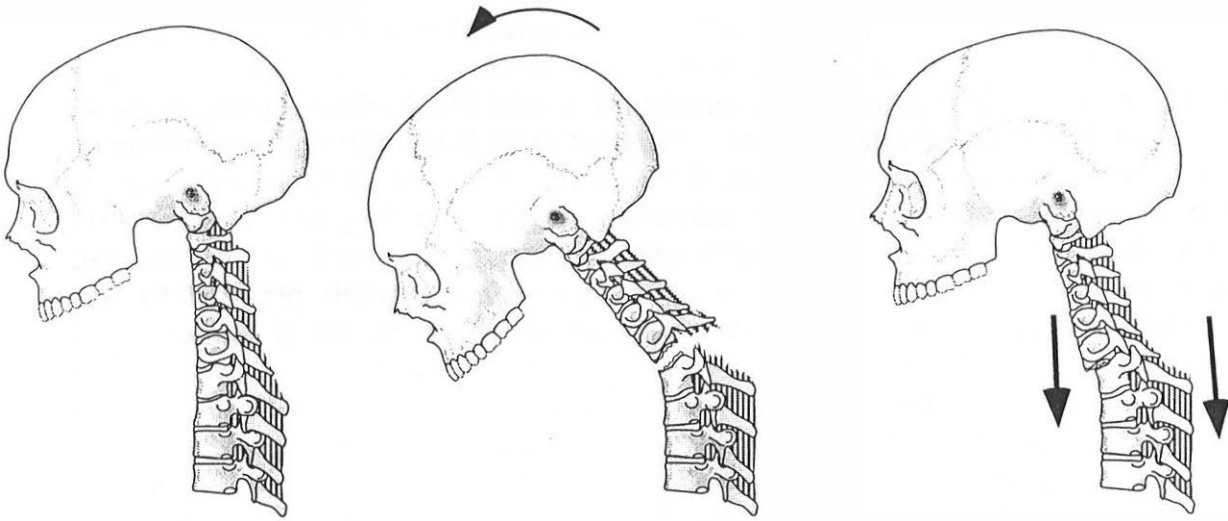


Figure 4: Mechanism of locked facet injury. This injury can be produced in either flexion-distraction or flexion-compression as long as the force vector to the head places the spine in a predominantly bending mode. First, the bending of the spine produces tearing in the posterior ligaments of one of the lower levels of the cervical spine mainly because the bending moments are highest in this region. Then as hyperflexion of the spine produces total disruption of the joint the reactionary response of the extensor and flexor muscles to stabilize the spine occurs and pulls down on the upper portion of the cervical spine. The downward contraction of the muscles at the time of hyperflexion of the spine slides the upper portion of the dislocated spine forward and down causing the superior facet to lock in front of the inferior facet.

specimens was 97 Nm. The neck load for these specimens was significantly higher however (mean = 3004 N). Both parameters performed well in a logistic regression test to describe the probability of major neck injury. A combination of bending moment and neck force may be needed to truly differentiate flexion-related injuries. This present study offers techniques and biomechanical parameters useful for defining injury tolerance of the human cervical spine to hyperflexion.

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