Neck kinematics in rear-end impacts

King H Yang / Albert I King*

Abstract
The purpose of this study was to document the kinematics of the neck during low-speed rear-end impacts. In a series of experiments reported by Deng et al. (2000), a pneumatically driven mini-sled was used to study cervical spine motion using six cadavers instrumented with metallic markers at each cervical level, a 9-accelerometer mount on the head, and a tri-axial accelerometers on the thorax. A 250-Hz x-ray system was used to record marker motion while acceleration data were digitized at 10,000 Hz. Results show that, in the global coordinate system, the head and all cervical vertebrae were primarily in extension during the entire period of x-ray data collection. In local coordinate systems, upper cervical levels were initially in relative flexion while lower segments were in extension. Facet joint capsular stretch ranged from 17 to 97%. In the vertical direction, the head and T1 accelerated upward almost instantaneously after impact initiation while there was delay for the head in the horizontal direction. This combination was the result of a force vector which was pointed in the forward and upward direction to generate an extension moment. Upward ramping of the torso was larger in tests with a 20-deg seatback angle. The study concluded that the kinematics of the neck is rather complicated and greatly influenced by the large rotations of the thoracic spine. Significant posterior shear deformation was found, as evidenced by the large facet capsular stretch. Although the neck forms a "mild" S-shaped curve during whiplash, using its shape as an injury mechanism can be misleading because the source of pain is likely to be located in the facet capsules.

Introduction
The term whiplash injury has been a controversial subject. According to the Collegiate Dictionary published by Merriam-Webster Inc. (Springfield, MA, USA), the term whiplash is defined as the lash of a whip. The dictionary further provides the "definition" of whiplash as an injury resulting from a sudden sharp whipping movement of the neck and head (as of a person in a vehicle that is struck head-on or from the rear by another vehicle). While this definition is not entirely correct, none was able to come up with a better term to describe this ailment. Other languages are not doing any better. Neither the French word "coup du lapin" nor the German term "schleudertrauma" provides any better definition. In a 1995 publication, the Quebec Task Force Team recommended the use of Whiplash Associated Disorders (WAD) to describe clinical syndromes most commonly associated with low speed rear-end impact (Spitzer et al., 1995).

The weight of the human head is approximately 4.5 kg (10 pounds). The neck (cervical spine), which is much smaller in diameter and lighter in weight than the head, supports the head and yet is flexible enough to allow a significant amount of motion in all directions. When subject to loading such as automotive crashes, the neck can easily be injured. Among the various field and experimental studies, the incidence rate of WAD varied widely from zero to 90%. In Lithuania, WAD problems did not seem to exist (Schrader et al., 1996), suggesting that financial reasons might play a role in the high percentage of injury claims in western society. Data from "Traffic Safety Facts 1995" show that, among passenger car and light truck crashes, rear-end collisions accounted for 20.7-21.2% of all accidents and usually resulted in so-called “whiplash” injuries in the United States (NHTSA, 1996). In Japan, approximately 50% of car-to-car accidents result in neck injuries, and the rate has moved upward continuously (Ono and Kanno, 1997). A Swedish research study showed that approximately 60% of injuries due to vehicle crashes causing disability in Sweden between 1990 and 1995 were whiplash injuries (Krafft, 1998). This number was much higher than that of 30% reported between 1976 and 1978 for the same country. In the United Kingdom, an emergency department reported that 65% of motor vehicle crash victims sustained neck injuries (Olney and Marsen, 1986). The highest rate reported came from a series of 25 km/hour rear-end impact cadaveric tests. Clemens and Burow (1972) found that 90% of test subjects in the group without a headrest sustained injuries in the form of cleavage of the intervertebral discs. To confuse matters even further, some studies have suggested that whiplash injuries also occurred in frontal as well as lateral impacts (Galasko et al., 1994, Larder et al., 1985, Morris and Thomas, 1996, Schneider et al., 1975).

There are many reasons why the incidence rate of WAD varied so widely from one study to another. But, the major reason is probably due to the fact that there are no available diagnostic techniques to provide evidence of the injury. Most whiplash injuries do not involve bony tissues and it is believed that the injuries are in the soft tissues (Compton, 1993, Walz and Muser, 1995, Squires et al., 1996). Despite the lack of objective evidence, many potential injury mechanisms have been suggested. Most of these mechanisms are based on observed kinematics of the neck in impacts on animals, cadaveric specimens, or volunteers.

Earlier studies have suggested that neck hyperextension may be responsible for WAD, based on the large extension angle of the neck in the later stages of a rear-end impact (Macnab 1964, Ommaya et al., 1966, States et al., 1969). However, the mandatory head restraint systems designed to prevent hyperextension of the neck did not completely eliminate this so-called whiplash injury (Morris and Thomas, 1996, O’Neill et al.,...
A popular hypothesis for WAD is muscle injury during which the anterior or posterior cervical muscles are injured when they undergo an eccentric contraction (Garrett et al., 1997, Tencer et al., 1999). However, animal studies have shown that injury to strained muscle repairs itself to a nearly normal stage in a few days (Nicolaau et al., 1987). Thus, although muscle injury may occur in a whiplash, it does not result in chronic neck pain. Radanov et al. (1995) reported that about 80% of occupants with WAD recovered within 16 months with the majority of these patients healing in the first six months. The remaining 10 to 20% of victims developed long-term WAD. It is in this group that long-term suffering is accompanied by large societal costs.

Another popular hypothesis proposed by Aldman et al. (1986) was based on an increase in pressure in the spinal canal during whiplash causing compression on the nerve roots. Subsequent experimental studies using pigs suggested that this pressure could affect the dorsal root ganglion (DRG) causing it to send pain signals to the brain (Svensson et al., 1993). Further studies by this Swedish group resulted in a formula called neck injury criterion (NIC) which related pressure increase with the relative acceleration and velocity between the head and torso (Bostrom et al., 1996). The formula for NIC was based on the flow of cerebral spinal fluid in the space between the cord and the dura but no evidence of the existence of a pressure gradient or of flow was ever presented. Clinically, stimulation or pressure on the nerve roots and DRG can produce radicular symptoms and not pain in the neck. Furthermore, a generalized increase in spinal canal pressure cannot selectively affect the nerve roots and DRG in the lower cervical spine where most of the problems appear to reside. Thus, although NIC may be meaningful in mechanical terms, the hypothesis it is based on does not fit symptoms that are commonly seen in whiplash victims.

The brain interprets acute pain from the signals it receives from a network of pain-sensing nerve endings or nociceptors that are found throughout the body. In the spine, the intervertebral disc nociceptors exist on its periphery. They are normally rather sparse and may not even be sensitive to mechanical loading. However, in a degenerated disc, nociceptors become more numerous and are sensitive to mechanical loading. Unfortunately, there are no valid diagnostic techniques that can ascertain the prevalence of disc lesion and WAD (Bogduk and Yoganandan, 2001).

On the other hand, clinical studies conducted in Australia by Barnsley et al. (1995) and Lord et al. (1996) have indicated that cervical facet (zygapophysial) joints are the single most common source of chronic neck pain after whiplash. It has been shown that facet joint capsules are richly innervated with nociceptors (Yamashita et al., 1990). Yang and King (1984) found that lumbar facet joints carry a significant portion of the total compressive load on the spine and hypothesized that the observed abnormal stretch of the facet joint capsule could be a source of low back pain. Using white New Zealand rabbits, Cavanaugh et al. (1996, 1997) was able to provide evidence to support the hypothesis proposed by Yang and King (1984). The authors further showed that low and high threshold mechanoreceptors fire when the facet joint capsule was stretched or was subjected to localized compressive forces (Avramov et al., 1992). The resulting tissue damage or inflammation was likely to cause release of chemicals irritating to the nerve endings in these joints, resulting in a sensitization of the nerve ending and, hence, low back pain (Ozaktay et al., 1994). Although similar neurological studies have not been done for the cervical spine, several studies have been conducted to link neck pain and facet joint deformation by studying cervical spine kinematics (Deng et al., 2000, Kaneoka et al., 1998, Ono et al., 1997, Yoganandan et al., 1998).

Ono et al. (1997) and Yoganandan et al. (1998) both proposed a facet joint impingement injury mechanism. Specifically, Ono et al. (1997) theorized that the facet synovium or a portion of the facet capsule could be trapped between the facet joint surfaces and pinched, causing pain. However, there is no biomechanical evidence that the capsule is loose enough to be trapped between the facet joint and even if it was trapped, evidence is lacking to show that nociceptors are present in the synovium or the trapped portion of the capsule that is indeed set off by the pressure. Kaneoka et al. (1998) hypothesized that the center of rotation moved superiorly during a whiplash and caused the tip of the inferior facet (of the upper vertebra) to impact the superior facet surface (of the lower vertebra). This proposition that compression of the facet surfaces can produce pain is probably untenable since cartilage is devoid of nociceptors and there is no neurophysiological evidence that the nociceptors in the subchondral bone can be made to fire by this presumed compression.

Another hypothesis related to the facet joint was proposed by Yang et al. (1997). The authors proposed that the combination of axial compressive force and posterior shear of the cervical spine induced a large stretch of the facet joint capsule. In a rear-end impact, the motion of the torso precedes that of the neck due to the fact that the force is first applied to the torso by the seat back. In order for the head to remain attached to the torso, a shear force is generated at each cervical level from C7 until it reaches the occipital condyles before the head can move forward. Because the cervical facet joint is inclined at an angle that is approximately 45 degrees from the antero-superior to posteroinferior position, this configuration makes it easier for the facet joint capsule to be stretched in a rear-end impact compared to that in frontal impact. The axial compressive force is due to straightening of the kyphotic thoracic spine and/or upward ramping of the torso on the seat back. Later, the hypothesis was modified to include the tensile force generated between the torso, which has been slowed down or stopped by the lap belt, and the head that is still moving in the superior-posterior direction. The following section presents results from a series of experiments carried out by Deng et al. (2000) to test this hypothesis.

Results of a Kinematic Study of the Neck
In 1998, a detailed finite element model representing the neck of a 50th percentile male was developed at Wayne State University (Yang et al., 1998). The model was validated against head and neck drop tests performed at Duke University (Nightingale et al., 1997) and data from three 24-km/h cadaveric rear-end impact tests. Results from the rear-end impact simulation predicted that the stretch in the C6-C7 facet capsule ranged from

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1972). Some recent studies have suggested that WAD may occur before the neck reaches full hyperextension (Bogduk and Yoganandan, 2001, Deng et al., 2000, Ono et al., 1997). So far, there is no single injury mechanism that has been identified to be directly associated with WAD, thus making it more difficult to design countermeasures to prevent this injury.
15 to 35%. The time traces for the predicted stretch in two elements of the C6-C7 facet capsule are shown in Figure 1.

Winkelstein et al. (1999) applied pure moments to cervical motion segments and used the term "subcatastrophic" to indicate the level of strain at which initial failure of the facet joint capsule occurred. The authors found a wide range of variation (67±77%) in the subcatastrophic strain and concluded that a small portion of the population may be at risk for this type of injury. However, the experiment was not a true simulation of whiplash. Results from the numerical simulation suggest that it would be worthwhile to continue the investigation of the proposed combined axial and shear force hypothesis.

In a series of low-speed rear-end impact tests reported by Deng et al. (2000), a portable HYGE mini-sled was designed and fabricated for use in the Motion Analysis Lab of Henry Ford Hospital (HFH), where a high-speed bi-planar x-ray imaging system is located. The system consisted of two x-ray generators and two photo-multiplier tubes which magnified the low light level produced by the system to allow two 250-frame/second (JC Labs HSC-250) x-ray video cameras to record the impact event. The sled consisted of a rigid seat with an adjustable seat back either with or without a head restraint. The sled was propelled by a pneumatic piston and glided on two 20-foot long rails.

A total of six cadavers, prepared according to the protocol reported by Cavanaugh and King (1990), were tested. Before testing, each cadaver was thawed to room temperature and anthropomorphic data were acquired. Each cervical vertebra (C1 to C7) was instrumented with 2 or 3 neck targets (2-mm diameter chrome steel or lead spheres) to facilitate tracking of vertebral motions recorded by the high-speed x-ray system (Figure 2). Nine accelerometers arranged in a 3-2-2-2 configuration were rigidly attached to the skull in order to measure the linear and angular accelerations of the head (Padgaonkar et al., 1976). Three accelerometers were attached to the thorax to measure linear acceleration components along three perpendicular directions in a body-fixed coordinate system at either the T1 or T2 vertebra. A total of 26 tests were conducted with velocities ranging from 1.4 to 4.3 m/s and accelerations ranging from 5 to 9.8 g's. A more detailed description of the experiment can be found in Deng (1999) and Deng et al. (2000).

Global Kinematics
Figure 3 shows a typical postero-anterior (X) and infero-superior (Z) acceleration traces measured at the center of gravity (CG) of the head and at the thorax from a typical cadaveric rear-end impact test. The impact was initiated at 97 ms after the start of data collection. It can be seen that there was a 24-ms delay for the thorax and a 104-ms delay for the head with respect to the sled. On the other hand, both the head and the thorax moved in the vertical direction as soon as the impact was initiated. It was also observed that the peak magnitude of the head and thorax accelerations were higher in the X direction as compared to that in the Z direction, indicating that the shear force component outweighed the axial force component. Additionally, because the thorax acceleration in the X direction started 80 ms before the head X acceleration, it provided evidence to support the hypothesis that shear force is transmitted from C7 to the occipital condyles, as stated previously.

Figure 4 shows movement of neck markers during a typical rear-end impact sled test. All markers moved in the anterior (to the right) and superior direction initially. Superior (upward) motion of the neck indicated that compressive force was generated in the neck between the upward moving torso and the stationary head. The reason for such motion is due to straightening of the curved spine and the upward ramping of the torso on the seat back.

Head and Cervical Spine Rotation
Based on the acceleration data shown in Figure 3, it could be deduced that the force vector on the thorax was directed forward (positive X) and upward (positive Z), thus it forced the head and neck into extension. Figure 5 shows the rotation of the head and cervical vertebrae in a test with a 20-degree seat back using a laboratory fixed coordinate system. It was found that the rotation for all cervical vertebrae and the head was mainly in extension with the head rotating much less than all cervical vertebrae. In terms of relative rotation of each cervical motion segment, Figure 6 shows that the upper cervical spine...
(C1-C2 and C2-C3) was in relative flexion while lower cervical spine (C4-C5 and C5-C6) was in relative extension. For C3-C4, there was a transition from extension to flexion or vice versa depending on the initial condition of the test. The absolute value of the peak relative rotation angle ranged from 2 to 17 degrees (Figure 7).

Axial Force and Torso Ramping
The vertical seat pan force was measured using a load cell. The initial load was balanced to zero before each test. A negative force (compression) indicated that the cadaver was moving into the seat. Both tests using either a vertical or a 20-degree seat back showed initial compression. This indicated that the lower torso was moving downward in the initial phase. From Figure 4, it was depicted that the neck was moving upward in the initial phase. Combining a downward movement of the lower torso and an upward movement of the neck, it was concluded that straightening of the spine occurred during the initial phase of a rear-end impact due to the seat back pushing on the thoracic spine. This phenomenon was discovered by BEGEMAN ET AL (1975) who observed thoracolumbar fractures in cadavers restrained by a double shoulder harness and subjected to frontal impacts.

Figure 3) Accelerations measured at the CG of the head and at the thorax in the postero-anterior direction (left) and infero-superior direction (right). Impact initiated at 97 ms after the data collection system was started.

Figure 4) Movement of neck markers during a rear-end impact test in a laboratory coordinate system. Positive X indicates movement in the anterior direction and positive Z indicates movement in the superior direction. Each trace indicates a neck marker initially located on the left side of the figure. More upward ramping of the torso occurred in the 20-degree seat back test, as demonstrated in the higher positive force measured in this test when compared to data obtained from the vertical seat back test (Figure 8). The seat back angle is also a possible contributor to this increased ramping. Additional evidence can be found from the movement of the pelvic marker (Figure 9). Both the vertical and 20-degree seat back tests showed backward and upward movement of the pelvis. The backward movement indicated that the lower torso was moving toward the seat.

Facet Capsular Stretch
Soft tissues, such as the facet joint capsule, cannot be displayed using x-ray devices. No marker was placed in the facet in order to avoid any disruption of the joint capsule. In order to calculate the percentage of the facet capsular stretch, positions of the superior and inferior facets of each vertebra was determined for each x-ray frame, assuming the facets to be rigid bodies. As shown in Figure 10, the origin of a body-fixed coordinate system was made to coincide with the posterior neck marker for each vertebra. The abscissa of the system was set parallel to the line from the posterior to the anterior marker while the ordinate was made perpendicular to the abscissa. At time zero, the coordinates of a point near the articular surface of both superior and inferior facets for each vertebra were recorded. These coordinates were used to calculate the position of each facet landmark based on the rigid body translation and the rotation of the coordinate system determined from the cervical spine markers. Engineering strain ($\Delta L/L$) was calculated at all time steps for comparison.

Substantial strains were found in all these tests. In 20-degree seat back tests, the average of the peak strain was 32±11% for the C2/C3 facet joint (17%-43% range), and 59±26% for the C3/C4 facet joint (41%-97% range). The peak strain for the C4/C5 and C5/C6 facet joints exhibited either tensile or compressive strains in different specimens. Thus, average values were not attempted. In 0-degree seat back tests, the average of the peak strain was 28±11% for the C2/C3 facet joint (21%-41% range), 30±9% for the C3/C4 facet joint (21%-39% range), 22±4% for the C4/C5 facet joint (19%-25% range), and 60±13% for the C5/C6 facet joint.
It should be noted that strain data reported here were calculated by dividing the change of length to the original length between the two facet landmarks. Thus, the initial distance between two adjacent facet markers could greatly influence the outcome of the strain reported.

Discussion and Conclusions
The advantage of using the high-speed x-ray system in conjunction with imbedded neck markers was that neck kinematics could be accurately studied. However, only low speed impacts could be studied due to the limited size of the x-ray image intensifier. Nevertheless, the system was able to handle speeds of up to 4.3 m/s (15.5 km/hour) while capturing all essential movements of the neck in the initial stage. Figure 11 shows a typical strain plot calculated from a C5-C6 motion segment. The peak facet capsular strain occurred before the head contacted the headrest. If indeed the underlying mechanism of whiplash injury is in the facet joint, data reported by Deng et al. (2000) summarized in this paper indicate that injury may have occurred in the very early phase of the impact. Other researchers have also concluded that whiplash injury may occur at a very early stage (Bogduk and Yoganandan, 2001).

The kinematics of the neck during a rear-end impact are very complicated. The neck experienced compression, tension, shear force, flexion, and extension at different stages and at different levels of the neck. Compression of the neck was due to straightening of the thoracic spine and the upward ramping of the torso with respect to the stationary head. Tension occurred immediately after the compression ended. The upward moving torso generated compression in the neck and eventually accelerated the head in the superior direction. As a result, tension occurred in the neck because the head moved relatively faster than the torso which was restrained by the lap belt.

Relative flexion occurred in the upper cervical spine and relative extension occurred in the lower cervical spine with the transition occurring in the middle cervical spine. Many researchers refer to this phenomenon as the formation of an “S-shape” in the cervical spine (Walz and Muser, 1995). However, the observed curvatures were mild and did not actu-
ally resemble the letter “S”. Based on initial compression and extension observed in the global coordinate system of the cervical spine, it is obvious that studies using isolated head and neck preparations tested on mini sleds (Panjabi et al., 1998a, 1998b, Cholewicki et al., 1998, Yogianandan et al., 1998) are not capable of capturing the complex kinematics of a whiplash test.

Posterior shear forces are generated in the neck when the torso moves forward due to an impact from behind by the seat back. The shear force is transferred from the lower cervical vertebrae to the upper ones through the soft tissues between adjacent vertebrae, one level at a time. This shear motion contributes to the straightening of the lordotic curvature of the neck before the torso moved ahead of the neck. The shear force occurring at the junction of the thoracic and cervical spine generates a flexion moment on the whole neck. The flexion moment is higher at higher cervical levels due to longer moment arms.

Biomechanical investigation on the human neck reported in this paper supports the hypothesis that WAD are caused by a combined axial and shear force acting on the facet joint. However, until neurophysiological studies of the cervical facet joint capsules are completed, readers need to recognize that it remains a hypothesis. Nevertheless, clinical treatments using percutaneous radio frequency neurotomy on patients who have facet (zygapophysial) joint pain have succeeded in providing long-term pain relief in patients with chronic pain (McDonald et al., 1999). It is concluded that the combined axial and shear force hypothesis is a likely cause of soft tissue injury to the intervertebral joints of the cervical spine. More research is needed to continue testing of this hypothesis.

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