SINGLE REAR IMPACT PRODUCES LOWER CERVICAL SPINE SOFT TISSUE INJURIES

Narayan Yoganandan, Frank A. Pintar, Brian D. Stemper,
Joseph F. Cusick, Raj D. Rao,* Thomas A. Gennarelli

Department of Neurosurgery
Medical College of Wisconsin, Milwaukee, WI, USA

*Department of Orthopedic Surgery
Medical College of Wisconsin, Milwaukee, WI, USA

ABSTRACT

A hallmark of injury biomechanical investigation is the production of injury to human surrogates and derivation of variables that quantify or explain the mechanism of trauma. This study was based on the concept that motion and injury are interrelated. In the first phase, post mortem human subjects were subjected to single rear acceleration using a sled. These tests were done to determine soft tissue-related injuries. Cryomicrotomy techniques were used because x-rays cannot directly document these types of injuries. In the second phase, head-neck complexes were tested in rear impact using a mini-sled pendulum. Injuries determined from intact tests were evaluated with kinematic parameters obtained from head-neck complex tests. Injuries (first phase) were primarily confined to the facet joints of the lower cervical spine and anterior column trauma. A majority of trauma was concentrated at the C5-6 level. Mechanically supporting evidence was observed in the kinematics of the cervical joints (second phase), wherein the C5-6 level responded with higher magnitudes of motions (than at other levels) associated with sliding and facet capsule stretch. Accentuated motions at lower levels explain injuries to the lower cervical spine seen in the form of soft tissue injuries due to single rear impact. This investigation indicates that neck pain may arise due to abnormalities of the intervertebral joints at the lower spinal level, as these soft tissues are replete with nociceptors.

Key Words: Biomechanics, soft tissues, neck, rear impacts, whiplash

SOFT TISSUE-RELATED NECK INJURIES sustained during rear-end automobile collisions continue to be a problem in western countries. These injuries are generally classified at the low end of the Abbreviated Injury Scale (AIS=1) category. Minor (AIS=1) neck injuries are among the most commonly reported injuries associated with low-speed, rear-end crashes. The estimated annual cost exceeds $4.0 billion in the United States (Yoganandan et al., 1999). The socioeconomic losses for rear-end crashes in Germany amount to approximately two billion marks and United Kingdom £2.5 billion. In Europe, each year, whiplash injuries alone costs insurance companies 10 to 20 billion DM. These staggering cost estimates render soft tissue injury research a high priority.

From an epidemiological perspective, 86% of all neck trauma results from vehicular crashes, and 80% of these injuries are secondary to rear-end impact (Foreman and Croft 1995). European data have indicated that the risk of sustaining an initial soft tissue neck injury is higher in rear-end than in other impacts. An English study reported that the injury risk is 38% in rear impact compared to 15% each in frontal and lateral crashes (Morris and Thomas 1996). Swedish researchers reported that soft tissue neck injuries leading to disability occur 64% in rear, 23% in frontal, and 9% in side crashes (Krafft et al., 1997). Statistical data show an increase in neck injuries in the last decade. The annual number of neck injuries in rear crashes is reported to have increased by 54% over a nine-year period in The Netherlands (van Kampen 1993), and doubled in Germany and United Kingdom over a decade (Langwieder and Hell 1996; Morris and Thomas 1996). Accentuation of these injuries underscores a need to determine their mechanism of production and the associated biomechanical variables.

From a clinical perspective, specific objective injury diagnoses do not exist. In fact, the spine is considered normal for the age of the patient; computed tomography (CT) and magnetic resonance images are negative for acute pathology (Yoganandan and Pintar 1998). Spinal alignment and instability are not compromised in these patients. Immediate surgical exploration is also not an option. Despite these "insignificant" diagnostic findings and lack of operative treatment regimen, complaints of neck pain and headache are common. The elusive nature is a constant source of confusion in the science of the injury. Laboratory-driven biomechanical research is necessary to clearly delineate lesions that may exist in the cervical structures.

From the perspective of delineation of biodynamics, testing of human volunteers has proliferated in the past decade (DeRosia and Yoganandan 2000). By definition and due to ethical reasons, tests can only be done at sub-injury levels using volunteers. Post mortem human subjects (PMHS) are routinely used to produce injuries and quantify the associated biomechanical metrics for correlation. Although this approach has been very successful in impact-induced trauma to the neck, inertial loading of the head-neck complex, which occurs in rear-end crashes, has not received similar attention (Yoganandan and Pintar 2000). A principal difficulty has been the production and identification of soft tissue injuries, determination of the associated of the injury metrics (e.g., kinematics), and their correlation to clinically reported neck pain. This is because x-rays and CT scans used commonly for diagnosis are unreliable for soft tissue trauma identification as they primarily depict the status of bony damage and spinal alignment. Therefore, a need exists to identify and quantify soft tissue injuries to the neck.

The present study is designed to address some of the above issues. It is developed on the concept that motion and injury are interrelated. The underlying basis lies in the anatomy and architecture of cervical spine joints that serve multiple roles. The joints allow motion, maintain spinal alignment, stability, and function. Protection of neural structures is another important function. It is critical to maintain interrelationships among the various cervical components under normal physiological and traumatic conditions. Intervertebral motions play a dominant role in spinal stability and function. Interrelationships are compromised in physiological situations (such as the aging process leading to radiculopathy and myelopathy). Clinical literature is replete with studies delineating abnormal motions of the cervical spine under these circumstances. To relieve pain, reduction or elimination of motion at affected levels of the spine is attempted using stabilization techniques. Therefore, an extension of the concept, i.e., pain stemming from abnormalities manifested secondary to motion, has a scientific basis when applied to dynamic conditions. In traumatic situations such as vehicular impacts, structural abnormalities ensue when motions of the intervertebral joints exceed their threshold. This may lead to pain if the components (e.g., facet joints) involved contain pain sensitive structures. The present study was conducted to investigate whether pain sensitive structures sustain abnormality secondary to motion, and characterize motions of these pain-related components in an attempt to correlate with clinical pain. This biomechanical study was conducted using PMHS.

METHODS

INTACT TESTS

In the first phase of the experimental design, intact PMHS (specimens) were tested using a sled to determine injuries to the head-neck complex under rear impact acceleration. Pretest x-rays were obtained to ensure the absence of preexisting trauma or metastasis. The specimens were prepared with tight-fitting leotards and placed on a custom-designed seat. The seat was fabricated from steel such that the panel where the pelvis and upper portions of the lower extremities were inclined 10 deg. Two parallel struts that braced the seat back prevented rearward motion of the seat.

The seat was rigidly attached to the base of the sled to apply rear impact acceleration. Figure 1 illustrates the schematic of the seat. No head restraint was used.

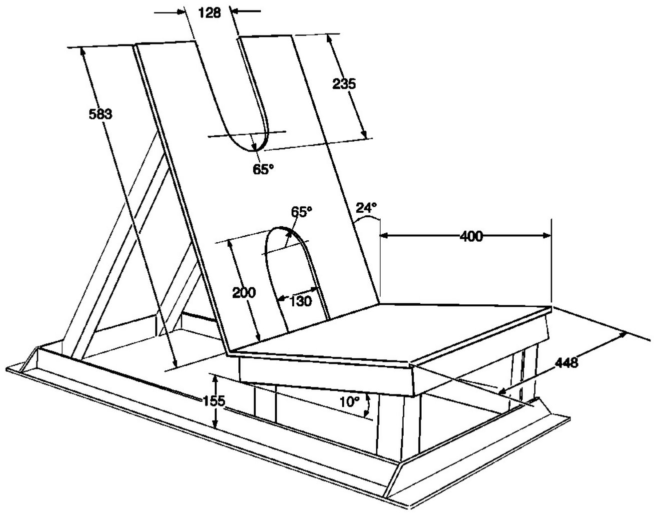

Figure 1: Schematic of the seat used in the study.

The leotard-clothed specimens were placed on the seat, and the knee-foot-ankle region of the extremities was extended. The Frankfort plane was horizontal, and the head was facing forward. Upper extremities were crossed in front of the thorax. The mastoid process of the skull was aligned vertically over the posterior margin of the first thoracic vertebra. A radiograph taken in this position corresponded to the orientation of the occipital condyles aligned over T1. A three-point belt restrained the torso. The lap belt had no slack. Cinch plates were used to lock the restraint. As soon as acceleration was imparted to the specimen, the inertial device that supported the specimen moved away without affecting head-neck kinematics. High-speed photography confirmed the action of the device. All specimens were tested once at a predetermined velocity of either 4.4 or 6.9 m/s. After the test, x-rays and CT images at 1.0-mm intervals were taken in the axial and sagittal planes. Sequential anatomical sections were obtained at intervals of 15 to 30 microns using a cryomicrotome device to parallel CT scans (Yoganandan et al., 2000). Overall and close-up color photographs of the hard and soft tissues were taken to identify injuries sustained by the specimen.

HEAD-NECK COMPLEX TESTS

In the second phase of the experimental design, a separate group of specimens were tested using a custom-designed mini-sled pendulum device to quantify kinematics of the cervical spine. Intact head-neck complexes were fixed using polymethyl-methacrylate. Posterior soft tissue structures including the ligamentum nuchae and skin were not dissected. A small area of tissue was carefully reflected locally in the lateral region to insert retroreflective targets. Targets were inserted to track relative rigid body displacements and rotations of the bony elements of the head-neck complex. Two targets were placed along the Frankfort plane (line passing through the auditory meatus and inferior orbit) and in the anterior vertebral body and lateral mass. Two pairs of targets were placed along the inferior and superior facet joint surfaces to define relative facet joint motions. The Cartesian system of reference was used: posterior-to-anterior direction was the +x-axis, right-to-left direction +y-axis, and inferior-to-superior direction +z-axis.

Prior to rear impact acceleration loading, the preparation mounted on the mini-sled apparatus was positioned such that the Frankfort plane of the head was horizontal, and the mastoid process of the skull was aligned over the posterior line of the first thoracic vertebral body. This positioning allowed consistent initial alignment based upon readily distinguishable anatomical landmarks from specimen to specimen. These head-neck orientations and positioning paralleled those used in intact PMHS tests described above. The initial alignment was ensured using a breakaway tape, which permitted free movement of the head-neck complex after event start. A 0.6 m/s run was performed twice at the start of the experiment to describe baseline motions, and once between each higher velocity test (1.3, 1.8, 2.6, and 3.5 m/s) for comparison and quantitative repeatability analysis. After each run, input pulses were analyzed for consistency between changes in velocity, pulse width, and maximum g-levels. Between tests, the specimen was visually inspected, and radiographs were taken.

High-speed cameras (1000 frames/second) were used to determine overall and local kinematics of the head-neck complex during loading. Target data from each level of the spine were analyzed for translation and rotation motions. Principles of continuous motion analysis were used to determine the kinematics of the head-neck complex. These motions were divided into overall, segmental, and local component kinematics. Local component motions were analyzed to achieve the objectives of the study. Facet joint motions were obtained in laboratory and local anatomical coordinate systems using the two pairs of targets placed on the rostral and caudal regions of the lateral mass. Local coordinate systems separately defined for each facet joint were used for analysis of these component motions. In addition to the x- and z-motions, resultant motions (stretch) and shift direction at the dorsal and ventral regions of the facet joint were obtained. Thus, an evaluation of the local component motions of the disc and facet joints was accomplished as a function of spinal level and velocity. Statistical analyses were done using the analysis of variance techniques (repeated ANOVA measures). In addition, average values of the various biomechanical variables were computed.

RESULTS

INTACT TESTS

In the first phase of the research, four specimens were evaluated for soft tissue injuries. The age ranged from 58 to 89 years of age. All were females except specimen C (Table 1). Three specimens (A, C, and D) were tested at a mean acceleration level of 4.5 g (delta V=6.9 m/s, high velocity). One specimen (B) was tested at 3.3 g (delta V=4.4 m/s, low velocity). Structural alterations occurred to mid-lower cervical spine components in all specimens. Abnormalities included stretch and tear of the anulus, ligament rupture, and facet joint compromise with tear of the capsular ligaments. Compression-related bony fractures did not occur in any test. One specimen tested at the high change in velocity sustained a mild avulsion of the anterior-inferior tip of C5 (Table 1). In addition, the anterior ligament was stretched at the C5-6 disc space at the distal body level, and diastasis of the right C5-6 facet and atlantal-axial joints with associated capsular tears occurred to this specimen. In another specimen tested at high velocity, soft tissue distraction was identified at the C5-6 intervertebral disc space. Additional soft tissue-related pathology included abnormalities in the anterior and posterior columns at the lower cervical level. Figure 2 illustrates the soft tissue structural alterations secondary to single application of rear impact in a specimen. Soft tissue injury descriptions on a specimen-by-specimen basis are included in Table 1. Mid-lower cervical spine, particularly the C5-6 level (Figure 2), was identified to be the most common region of soft tissue injury.

Table 1: Summary of Pathological Findings

ID	Findings
A	C5-6 anulus and anterior longitudinal ligament tear, and the separation of the 6-7 flavum with anterior displacement into the spinal canal.
B	C5-6 facet joint joint capsular ligament tear on the right side of the specimen. In addition, the C6-7 flavum separated from the C7 lamina.
C	C5-6 disc disruption and anterior longitudinal ligament rupture, and mild tear of the ligamentum flavum. Facet joint capsule tear at the C5-6 on the right side. In addition, widening of the C4-5 facet joint on the left side.
D	C5 vertebral body avulsion and anterior ligament tear, C5-6 facet joint widening on the right side and ligament tear, and right atlantal-axial joint with hematoma of the joint with ligament tear.

Figure 2: Cryomicrotome image illustrating the diastasis of the C5-6 facet joint (arrow). Capsular ligaments were torn at this level at the anterior and posterior regions of the joint.

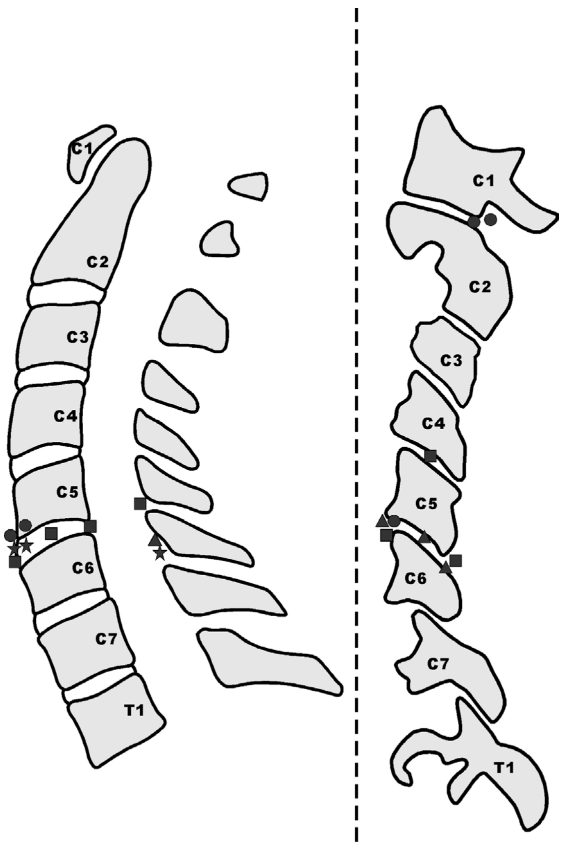

Figure 3:. Facet joint injuries are shown in the parasagittal (right), and other injuries are shown in the midsagittal section (left). Note the concentration of injuries at the C5-6 level.

HEAD-NECK COMPLEX TESTS

In the second phase, eight head-neck complexes were tested. The age ranged from 51 to 84 years of age. Analysis of facet joint motions in the mid-lower cervical spine regions indicated that the joints slide from the anterior to the posterior (along the facet joint line) direction. There were no statistical differences ($p<0.05$) between anterior and posterior sliding motions of the joints, i.e., this component motion was uniform across the articular surface of the lateral mass. The direction of resultant motion was statistically significantly different between the anterior and posterior edges of the facet joint (Figure 4). Local x-axis in the figure is defined as the line along the facet joint in the posteroanterior direction. The direction of motion in the anterior region was less than 180 deg from the local x-axis (180 deg defined as pure anteroposterior sliding along the line of the facet joint). This indicated an anterior-to-posterior sliding and local z-axis distraction of the joint. In contrast, the posterior region of the facet joint resulted in a direction of motion greater than 180 deg (Figure 5). This corresponds to anteroposterior sliding with compression along the local z-axis. The difference in motion direction between the anterior and posterior regions of the facet joint was statistically significant ($p<0.001$) at all investigated levels of the cervical spine. Facet joints stretched in the plane perpendicular to the joint in the anterior-most region (significantly different, $p<0.05$, from the posterior motion). In general, at all velocities, the C5-6 facet joint showed increased resultant motion (stretch) compared to its inferior and superior spinal levels. This was independent of the location of the facet joint, i.e., posterior versus anterior region. Figure 6 illustrates mean resultant facet joint stretch kinematics as a function of mid-lower cervical spine levels.

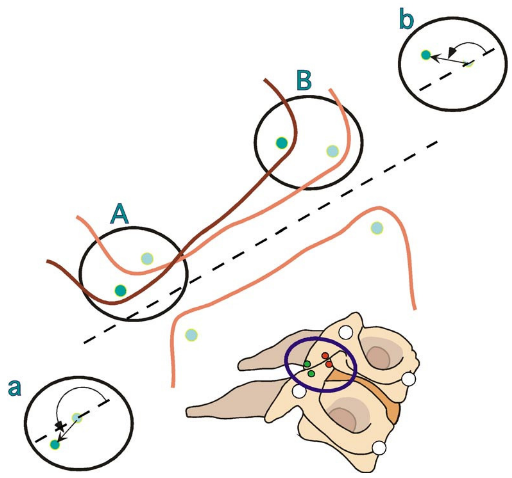

Figure 4: Diagram illustrating facet joint motion. Lighter lines denote the initial orientation of the facet joint. Darker line shows the movement of the superior surface of the facet joint with respect to the inferior surface. The dashed line shows initial angulation. Retroreflective targets inserted to the facet joint are shown in the functional unit. Angulation of the facet joint is defined as the vectorial orientation between the initial and final positions of the target (shown in circles) at the anterior and posterior regions with respect to the initial joint line. An angle greater the initial angle (180 deg) represents rearward motion of the particular region (e.g., anterior) of the joint. Inserts a (for A in the main figure) and b denote the vector directions of these motions at the posterior and anterior regions of the facet joint. Dashed line in the inserts are drawn parallel to the initial facet joint line shown as a longer dashed line in the main figure.

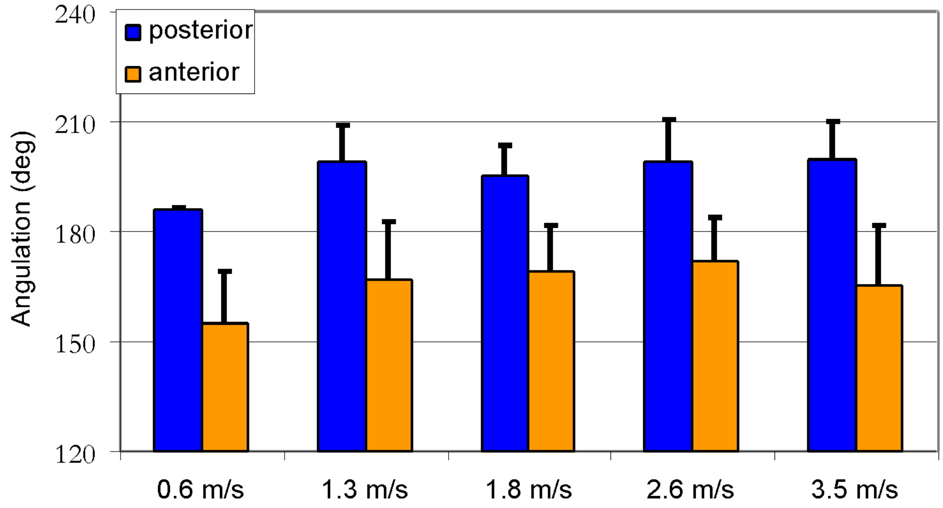

Figure 5: Mean resultant facet joint angulation in the lower cervical spine. See Figure 4 for details.

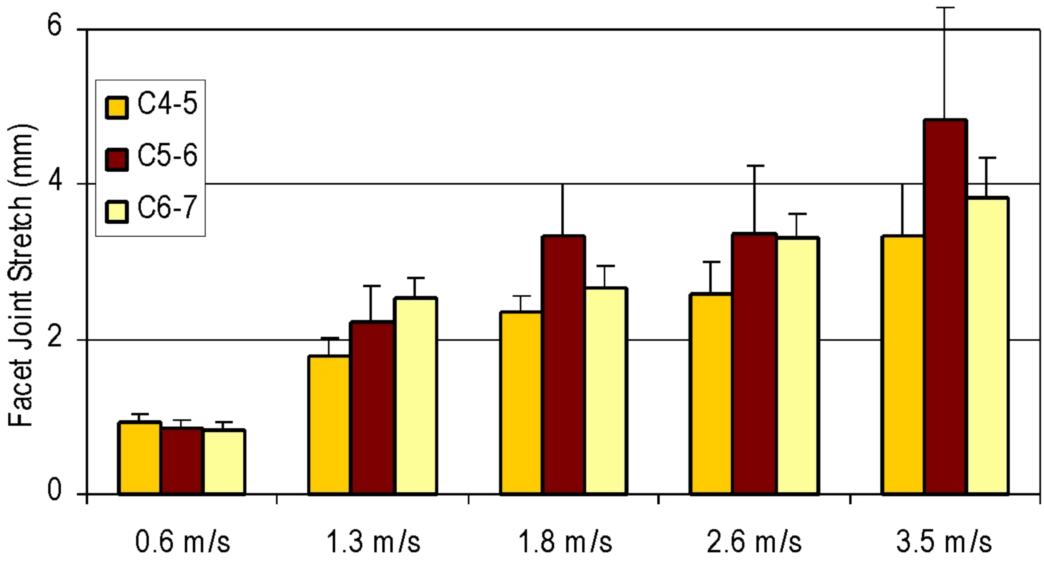

Figure 6: Mean resultant posterior facet joint stretch in the lower cervical spine. The resultant stretch includes both sliding and axial (components) motions in the capsule indicating the overall magnitude of posterior joint movement. Note that the C5-6 facet joint may be particularly susceptible to stretch.

DISCUSSION

LIMITATIONS AND COMPARISON WITH LITERATURE

The present study employed both whole-body and intact head-neck complexes for biomechanical analyses. The advantage of the former model is that the effects of all structures such as the thoracolumbar spine are included. In addition, application of a single cycle of loading delineates injuries that may mimic real world trauma. The advantage of the head-neck complex model is that microlevel-type kinematics can be derived which are difficult to extract from whole-body tests. Combining injuries with localized component-based kinematics, an approach used in this investigation has not been reported in literature, to the best of our knowledge. These are the strengths of the present study.

A criticism of the intact model is that the effects of active musculature are ignored. For dynamic loading conditions, it is generally acknowledged that muscle contraction occurs late in the dynamic event. A study examining neck electromyography signals during human volunteer rear-impact auto collisions reported that initial muscle activation does not occur until 100 msec after event start, and full muscle contraction does not occur until 150-170 msec after event onset when the head-neck is already in extension (Szabo and Welcher 1996). Similar findings have been confirmed by other human volunteer studies (Kaneoka and Ono 1998). Furthermore, animal experiments have demonstrated that the time to develop muscle force is approximately 200 ms (Tennyson and King 1973). The concept is that the initial injury occurs before this time and, therefore, active muscle contraction is not a primary determinant. This premise that, changes in the activation of muscles is of secondary importance in minor neck injuries in whiplash patients is more directly applicable to occupants who are unaware of the rear impact. In fact, studies have indicated that peak strains in the facet joints under whiplash loading occur before the head contacts the head restraint and before hyperextension (Deng 1999). Therefore, that without this protective component in the initial stages of rear impact acceleration, the head-neck complex could be susceptible to injury. In the living human, the head is held upright by activation of certain anterior and posterior muscle groups. These groups pre-align the head with respect to the neck before loading.

A criticism of the isolated model is that fixation at the distal end precludes the effect of upward motion and rotation of T1. This necessitates an intact human cadaver model to account for these effects. However, the present trend of accentuated motions in the lower spinal levels compares favorably with cineradiography-based tests (Deng 1999). A preliminary analysis of data (not directly pertinent to the objectives of the study) was performed to examine the correlation of intervertebral motions. At a sled velocity of about 1.8 m/s (T1 delta V was higher than sled delta V by approximately 35 percent), the cited study reported C5-6 and C4-5 rotations ranging from 2 to 14, and 5 to 10 deg; data were not reported at the C6-7 level. The values from the present study, at T1 delta V of 2.6 m/s were 2 to 13 and 3 to 9 deg, and these results correlated well with the previous study. These correlations suggest that contribution from the upward motion and rotation of T1 may be secondary, and the linear posteroanterior acceleration is the most important input in rear impact. All T1 delta Vs referred herein correspond to the horizontal component of the acceleration. In addition, it should be noted that the T1 accelerations imparted to the head-neck complex model in the present experiments included only the horizontal component because the base of the preparation was fixed. Pendulum accelerations represented the T1 acceleration-time histories. Since the objective of the study was not to evaluate the acceleration profiles from various studies, these issues are deferred to the future. Further, page limitations for this presentation was also a consideration. Detailed analyses of data such as acceleration values, their peak, pulse width and angular rotations (for example, mean and deviation) on a level by level basis as a function of impact velocity and their implication in whiplash injury are underway. After full analyses, these data will be reported in future publications.

This ongoing research attempted to determine statistical significance of the findings through repeated ANOVA measures. As indicated in the Results Section, all kinematic parameters did not reach significant levels ($p<0.05$). A clear trend was, however, demonstrated in others (resultant stretch motion in the facet joints as depicted in Figure 4). The size of the ensemble, together with biological variabilities, may have been most likely responsible for this lack of less than normally acceptable statistic. Tests from additional samples will reinforce the findings from a statistical viewpoint. This process is considered an extension of the present study.

CLINICAL RELEVANCE

The present study identified soft tissue-related anatomical abnormalities to facet and disc joint complexes of the cervical spine (Figures 2, 3 and Table 1). These structural alterations are pertinent in rear impact-induced minor neck injury.

Soft tissue injuries of the facet joints are clinically relevant. For example, these joints are replete with pain-sensitive structures. Pain patterns due to blockage of facet joints have been delineated using volunteers. Characteristic areas of pain referred from these joints correlate with those frequently exhibited by patients complaining of chronic neck pain (Bogduk 2000). Tears of the joint capsule have been reported on radiograms, and soft tissue-related lesions have been identified at autopsy in subjects with a diagnosis of hyperextension injury. Clinical studies have implicated facet joints as a source of pain in 30-40% of patients with chronic neck pain (Lord et al., 1996). In this previous study, patients sustained chronic pain (greater than three months) due to a motor vehicle crash; 56% of the occupants sustained rear impact. These results have been corroborated by showing that radiofrequency neurotomy is effective in relieving facet-induced neck pain. These data emphasize the role of facet joints in soft tissue neck injury.

Disc-related injuries are also clinically relevant. Cervical discs are supplied with nerves and mechanoreceptors. Nerve fibers enter the disc in the postero-lateral direction and traverse both parallel and perpendicular to the bundles of the anulus fibrosis. Non-encapsulated receptors include non-myelinated free nerve endings and terminals, and are either efferent vasomotor fibers or afferent pain receptors. Non-encapsulated nerve endings in the anulus fibrosis acting as pain receptors may explain the occurrence of neck pain secondary to soft tissue-related disc pathology. Pacinian corpuscles and unencapsulated joint receptors activate in response to changes in tension. Considering the structure of the cervical anulus, mechanisms of discogenic pain have been reported to include strain or tear of the anterior anulus and strain of the alar portions of the posterior ligament (Mercer 1999). Avulsions of the disc from the endplate of the vertebra and annular tears are termed as rim lesions. This injury clinically occurs in the rostral part of the disc with a tear near the attachment of the vertebral rim to the anulus. These issues underscore the role of the disc and ligament-related structures in soft tissue neck injury.

The soft tissue abnormalities identified in the cryomicrotome images are not discoverable in routine spine films. As discussed earlier, soft tissue abnormalities occur due to motions exceeding threshold. Soft tissue injuries may have long-term implications. For example, the initial injury causing structural lesions may predispose the spine to premature degenerative changes. This is supported by a study that found a high incidence of degeneration in surgical patients with a history of a previous traumatic event (Hamer et al., 1993). Age was significantly less ($p<0.05$) for those patients who recalled a previous traumatic event. The majority of procedures were performed at the lower spine, particularly C5-C6. The present finding of the involvement of the C5-6 spinal level for the existence of soft tissue injuries appears to support these findings and underscore the vulnerability of this region of the lower cervical spine in rear impacts.

MECHANISTIC ISSUES

The localized component kinematic changes observed in the present study, particularly the facet joint, indicated complex, non-uniform motions in the intervertebral joint. The sliding motions (x-axis, shear component) between the anterior and posterior regions of the facet (rearward kinematics) correspond to the local extension of the cervical spine. These motions were found to be similar in magnitude. However, axial motions (z-axis) differed between the anterior and posterior regions of the facet joint, indicating a dissimilar local facet joint axial response. The direction of the resultant motions (stretch in both anterior and posterior regions) of the facet joint (Figure 5) also showed a dissimilar behavior due to these changes in the shear and axial motions. Depending on the local threshold of the capsular ligaments, stretch beyond elastic limits or tear may occur in the anterior or posterior regions of the joint as both regions respond with joint stretch. Since these joints have pain fibers, local stretch may elicit pain.

Examining motion data from a local z-axis perspective, the localized compression of the posterior region of the facet joint together with the distraction of the anterior region directs toward a pinching mechanism for rear impact-induced pain proposed in literature. The posterior regions of the facet joint may come in contact with the subchondral bone via cartilage compression. Human volunteer tests have referred to this as facet impingement (Ono et al., 1999) or collision (Ono and Kaneoka 1997) mechanism. Mere compression of cartilage is inadequate to induce pain because it is deprived of nerve endings. However, cartilage degradation accentuate osteoarthrosis, leading to long-term changes in the mechanics of the innervated subchondral bone. The pinching action does not refer only to the axial component of the facet joint motion. The resultant motion of the anterior and posterior regions of the joint (axial and sliding motions) describes the stretch of the joint itself. Through an examination of the local and shear and axial components of motion, and resultant stretch motions, the present study offers an explanation for the abnormalities stemming from these joints of the spine.

Increased local spinal component motions at the C5-6 level suggest that this level is susceptible to trauma in rear crashes. As described above, intact specimen tests exhibited a frequent involvement of the C5-6 level in the production of the soft tissue injury (Table 1). Clinical studies, as discussed in the foregoing, clearly emphasize the role of these joints in chronic pain. Therefore, the two models are relevant and complimentary in terms of injury production, documentation, and kinematics. Evidence of soft tissue-related injuries of the lower cervical spine secondary to single rear impact acceleration, and biomechanical explanation for the probable cause of these injuries through kinematic analysis, are offered through this study.

CONCLUSIONS

This biomechanical study was based on the concept that motion and injury are interrelated. In the first phase, post mortem human subjects were subjected to single rear acceleration. Cryomicrotomy techniques determined soft tissue-related injuries. In the second phase, head-neck complexes were tested in rear impact using a mini-sled pendulum. Injuries determined from intact tests were evaluated with kinematic parameters obtained from head-neck complex tests. Injuries (first phase) occurred primarily to the facet joints of the lower cervical spine and anterior column trauma. A majority of trauma was concentrated at the C5-6 level. Mechanically supporting evidence was observed in the kinematics of the cervical joints (second phase), wherein the C5-6 level responded with higher magnitudes of motions associated with relatively uniform sliding, differing axial motions in the ventral and dorsal regions, and resultant facet capsule stretch. Accentuated motions at lower levels explain injuries to the lower cervical spine seen in the form of soft tissue injuries due to single rear impact. This investigation indicates that neck pain may arise be due to abnormalities of the intervertebral joints at the lower spinal level, as these soft tissues are replete with nociceptors.

ACKNOWLEDGMENTS

This research was supported in part by PHS CDC 515433 and VA Medical Research.

REFERENCES

Bogduk, N. An overview of whiplash. Frontiers in Whiplash Trauma: Clinical & Biomechanical. N. Yoganandan and F. Pintar. The Netherlands, IOS Press: (2000) 3-9.

Deng, B. Kinematics of human cadaver cervical spine during low-speed rear-end impacts. Biomedical Engineering. Detroit, MI, (1999) 239.

DeRosia, J. and Yoganandan, N. Lessons from staged rear-end collisions using human volunteers. Frontiers in Whiplash Trauma: Clinical & Biomechanical. N. Yoganandan and F. Pintar. The Netherlands, IOS Press: (2000) 265-294.

Foreman, S. M. and Croft, A. C. Whiplash Injuries. The cervical acceleration/deceleration syndrome. (1995) Baltimore, MD, Williams & Wilkins.

Hamer, A. J., Gargan, M. F., Bannister, G. C. and Nelson, R. J. “Whiplash injury and surgically treated cervical disc disease.” Injury **24**(8): (1993) 549-550.

Kaneoka, K. and Ono, K. Human volunteer studies on whiplash injury mechanisms. Frontiers in Head and Neck Trauma. N. Yoganandan, F.A. Pintar, S.J. Larson, and A. Sances, Jr.,. The Netherlands, IOS Press**:** (1998) 313-325.

Krafft, M., Kullgren, A., Lie, A., Nygren, A. and Tingvall, C. "Soft-tissue injury of the cervical spine in rear-end car collisions." J of Traffic Medicine **25**: (1997) 3-4.

Langwieder, K. and Hell, W. Neck injuries in car accidents-causes, problems and solutions. Int Conf on Active and Passive Automobile Safety, (1996) , 131-146.

Lord, S., Barnsley, L., Wallis, B. and Bogduk, N. "Chronic cervical zygapophysial joint pain after whiplash." Spine **21**(5): (1996) 1737-1745.

Mercer, S. "The ligaments and anulus fibrosus of human adult cervical intervertebral discs." Spine **24**(7): (1999) 619-628.

Morris, A. and Thomas, P. Neck injuries in the UK cooperative crash injury study. Proceedings of the 40th Stapp Car Crash Conf, (1996) Albuequerque, NM, 317-329.

Ono, K., Inami, S., Kaneoka, K., Gotou, T., Kisanuki, Y., Sakuma, S. and Miki, K. Relationship between localized spine deformation and cervical vertebral motions for low speed rear impacts using human volunteers. Proceedings of the IRCOBI Conf, (1999) Sitges, Spain, 149-164.

Ono, K. and Kaneoka, K. Motion analysis of human cervical vertebrae during low speed rear impacts by the simulated sled. IRCOBI Conference, (1997) Hannover, Germany, 223-237.

Szabo, T. J. and Welcher, J. B. Human subject kinematics and electromyographic activity during low speed rear impacts. Proceedings of the 40th Stapp Car Crash Conf, (1996) Albuquerque, NM, SAE Inc., 295-315.

Tennyson, S. and King, A. A biodynamical model of the human spinal column. Proceedings of the SAE Mathematical Modelling Biodynamic Response to Impact, (1973) Dearborn, MI, 31-44.

van Kampen, L. Availability and (proper) adjustment of head restraints in The Netherlands. Proceedings of the IRCOBI Conf, (1993) Eindhoven, The Netherlands, 267-378.

Yoganandan, N., Cusick, J. and Pintar, F. Whiplash injury (soft tissue) identification with conventional spine imaging and cryomicrotome. Proceedings of the 28th Cervical Spine Research Society Meeting, (2000) Charleston, SC, 114-115.

Yoganandan, N. and Pintar, F. Biomechanical assessment of whiplash. Frontiers in Head and Neck Trauma: Clinical and Biomechanical. N. Yoganandan, F. Pintar, S. J. Larson and A. J. Sances. The Netherlands, IOS Press**:** (1998) 344-376 pp.

Yoganandan, N., Pintar, F. and Kleinberger, M. "Whiplash injury - Biomechanical experimentation." Spine **24**(1): (1999) 83-85.

Yoganandan, N. and Pintar, F. A., Eds. Frontiers in Whiplash Trauma: Clinical and Biomechanical. (2000) . The Netherlands, IOS Press. 590 pp.