Neck Injury Criterion Based on Intervertebral Motions and its Evaluation using an Instrumented Neck Dummy

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ABSTRACT

A new neck injury criterion (IV-NIC) was developed. It was based on this hypothesis: *A neck injury occurs when an intervertebral rotation exceeds its physiological limit during whiplash.* An instrumented artificial cervical spine, incorporating human quantitative anatomy, kinematics and kinetics, was constructed. Twelve experiments were performed at 3 T1-accelerations and 4 initial head-headrest gaps. In general, IV-NIC and NIC increased with T1-accelerations. Both IV-NIC and NIC were highest at middle gap value. IV-NIC indicated severity, location and mode of injury. This comprehensive injury information is helpful in designing whiplash injury prevention systems, and for diagnosis and treatment of whiplash injuries.

UNDERSTANDING INJURY MECHANISM in whiplash trauma and defining a neck injury criterion are important research goals. The injury mechanism is complex and the soft tissue injuries occurring in whiplash are not readily observable by any imaging techniques in a clinical setting. One has approached these issues by conducting simulated whiplash experiments using human volunteers (Davidson et al.1998, Ono et al.1998, McConnell et al.1993), dummies (Seeman et al.1986, Hoofman et al.1998), mathematical models (Yoganandan et al.1998, Linder et al.1998), and whole cadavers (Eichberger et al.1998). Each of these approaches has well known advantages and disadvantages. Although much has been learned about the kinematics of the head and cervical spine during simulated whiplash trauma in the human volunteer experiments, yet the volunteers are not subjected to injury causing accelerations. Presently the available dummies do not adequately replicate the kinematics and kinetics of the human cervical spine, and additionally, they are incapable of measuring the injury. The mathematical models have the potential to appropriately simulate the real human being, however, there are significant problems with validation and injury detection. Although the injuries can be produced in whole human cadavers by appropriate whiplash simulations, quantifying the injury in whiplash trauma is still not possible in cadavers because of the subtleties of the whiplash injury.

In recent studies, human cadaveric spine specimens have been used in simulated whiplash trauma (Grauer et al.1997, Panjabi et al.1998b, Panjabi et al.1998c). The major advantages of this approach are the documentation of injury in real-time (Panjabi et al.1998b), and that the resulting injuries are quantified by measuring the physical properties of the spine specimen before and after the trauma (Panjabi et al.1998c). Furthermore, this approach allows one to identify the site and time at which the injury occurs, and whether the injury correlates to flexion or extension trauma mode (Panjabi et al.1998a, Grauer et al.1997).

There is a need for the development of an injury criterion that can be readily used by all types of whiplash trauma simulators to determine the occurrence of the injury to the cervical spine. The precise cause of short and long term neck injuries in whiplash trauma is presently not well understood, although certain characteristics of rear impacts are being identified (Kraft et al.1998, Temming et al.1998). One hypothesis is based on the *in vivo* observations in a porcine model that during whiplash of the neck the cerebral spinal fluid (CSF) pressure increases/decreases (Svensson 1993). Recently a neck injury criterion (NIC) has been presented on this basis (Bostrom et al.1996). Attempts have been made to validate this criterion using histology of porcine ganglia (Ortengren et al.1996), and whiplash studies using human volunteers (Eichberger 1998, Wheeler 1998), and whole cadaver experiments (Eichberger et al.1998, Wheeler et al.1998). In general, the calculated NIC values were shown to increase with increasing impact velocities. However, no definitive correlation was made between NIC values and actual clinical symptoms in whiplash trauma. Furthermore, the NIC formulation does not identify the site or mode of injury. Even if the NIC hypothesis based upon spinal fluid pressure changes is validated, there may be additional causes of whiplash related injury.

An alternative hypothesis for the injury mechanism may be formulated based on clinical observations of injury to the facet joints located in the posterior aspect of the cervical spine during whiplash trauma (Barnsley et al. 1995, Lord et al.1996). This mode of injury may be explained by the experimental observations of human spine specimens (Panjabi et al.1998a). This study indicated that the intervertebral motion was found to exceed the physiologic limits in extension mode, indicating high impact loads on the facet joints. This may explain the clinical observations of Barnsley et al.1995 and Lord et al.1996.

We hypothesized that a neck injury occurs during whiplash when the relative motion between vertebrae significantly exceeds the physiological limits. The purpose of our study was to define an injury criterion based upon this hypothesis and to evaluate it in simulated whiplash experiments.

METHODS

INTERVERTEBRAL-NECK INJURY CRITERION:

We propose a new injury criterion for the neck. It is based upon the hypothesis that the cervical spinal column is injured due to excessive physiological intervertebral motions during whiplash. The normal physiological ranges of motion (ROM) between adjacent vertebrae of the cervical spine have been measured in terms of angular rotation between adjacent vertebrae, using human cadaver specimens (Moroney et al. 1988, Panjabi et al., unpublished). From a neutral starting position, the ROM values are measured separately for extension and flexion. Average values from these measurements are shown in **Figure 1**.

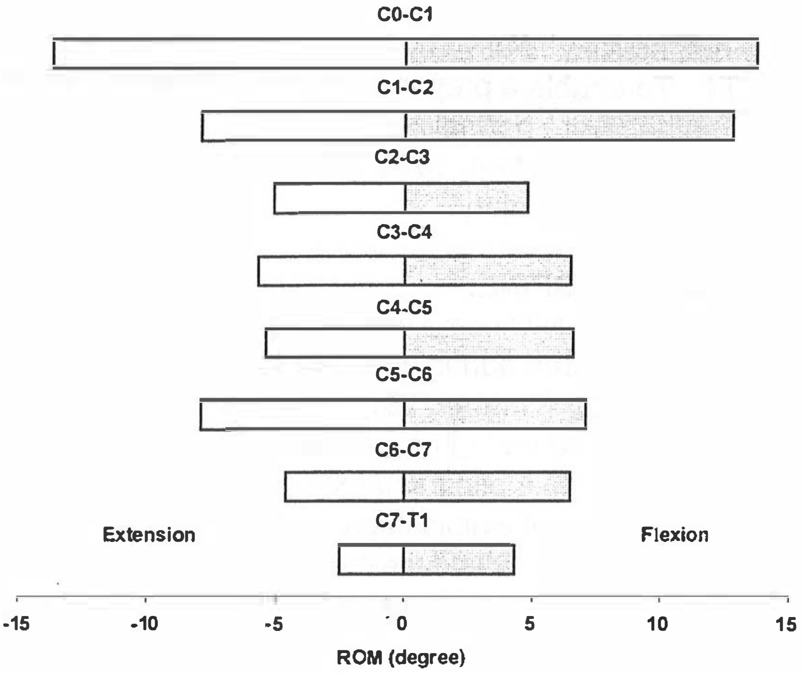


Figure 1: Physiological ranges of motion (ROM) of intervertebral joints.

The InterVertebral-Neck Injury Criterion (IV-NIC) is defined as the ratio of the intervertebral motion θ_{trauma} that occurs during the whiplash trauma to the physiological range of motion $\theta_{physiological}$. For each intervertebral joint between C0 and T1, the IV-NIC was calculated using the following formula:

$$\textbf{IV-NIC}_i = \theta_{trauma,\,i} / \theta_{physiological,\,i}$$

where subscript **i** indicates the intervertebral joint. As IV-NIC is a ratio it has no units of measurement. All intervertebral angles are measured from a neutral starting position, and the IV-NIC is calculated separately for flexion and extension. There is the potential for neck injury when there is an increase in the intervertebral motion at any spinal level which exceeds the physiological value. This is represented by IV-NIC values greater than one. For the overall severity of spine injury, the maximum IV-NIC value from all intervertebral levels may be used. The time, location, and mode (flexion or extension) at which the maximum IV-NIC value occurs can be identified. After the IV-NIC has been validated by *in vivo* biomechanical and clinical studies, it may be of use in the design of injury prevention devices and in diagnosing whiplash injuries clinically.

The IV-NIC criterion is based upon a physiological interpretation of the injury mechanism. This criterion has the advantage that it can identify the site and mode of injury, as well as the time of injury. The IV-NIC criterion is yet to be validated through correlation with actual whiplash injuries. Thus, no threshold value for IV-NIC is proposed at this time. Further research is needed in this area.

For the purpose of comparison we also computed NIC (Bostrom et al.1996), as defined by the equation below.

$$\mathbf{NIC = 0.2\ a_{rel} + v_{rel}^2}$$

where a_{rel} and v_{rel} are respectively relative horizontal acceleration and velocity between the C0 and T1. To enable a proper comparison between the two injury criteria, the NIC values were normalized by dividing by 15, the recommended injury threshold (Bostrom 1996), so that a value of one for the normalized NIC indicates potential injury.

ARTIFICIAL CERVICAL SPINE:

The advantages of the IV-NIC come with the requirement that the intervertebral motions be measured during whiplash traumas. In previous experiments with cadaver spines (Grauer 1997) visual flags were attached to each vertebra, and were recorded on high speed film. However, experiments with human cadavers are time consuming and expensive, and therefore are not suitable for parametric evaluation of whiplash prevention devices. Accordingly, a Whiplash Artificial Cervical Spine was developed at Yale (WACSY) . The WACSY was instrumented to measure intervertebral motions, and its geometry, kinematics, and kinetics were designed to mimic the human spine and its mechanical response, **Figure 2.**.

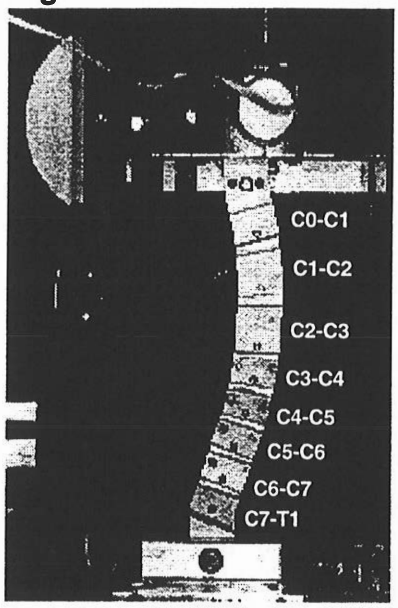


Figure 2. WACSY model consists of 7 vertebrae and a surrogate head.

The WACSY was constructed from aluminum blocks (vertebrae), connected in a serial manner via hinge joints, and rubber sheets (equivalence of elastic connections between adjacent vertebrae). The WACSY included all intervertebral joints from C0 - C1 to C7 - T1. It had vertebral geometry location of centers of rotation and stiffness properties respectively based on: *in vitro* measurements of cervical vertebrae (Panjabi et al.1991a), *in vivo* kinematic studies of volunteers (Dvorak et al.1991), and kinetic studies using *in vitro* human spine experiments (Panjabi et al., unpublished).

Use of IV-NIC requires that the intervertebral motions of the cervical spine be measured at all spinal levels (C0-C1 to C7-T1). This necessitated the development of special rotary transducers that were incorporated into the WACSY to measure the intervertebral rotations during the simulated whiplash.

Static calibration of WACSY: The WACSY was tested in the same flexibility machine as used for the testing of the cervical spine specimens, and was subjected to pure moments of flexion and extension up to 1.0 Nm (Panjabi et al.1991b). Intervertebral rotations were measured from the sensors located at each spinal level. We were successful in making the WACSY simulate the static human neck kinetics both *in vitro* (Panjabi et al., unpublished) and *in vivo* (Dvorak et al.1991), **Figure 3A.**

Dynamic validation of WACSY: The purpose of the validation was to compare the dynamic behavior of the WACSY to that of the human spine specimens in simulated whiplash trauma. Recently, several studies have been published from our laboratory that have documented the response of the human cervical spine specimens, with appropriate head surrogate, to whiplash trauma. One typical comparison of maximum rotations at 8 g acceleration shows good correlation between WASCY and human *in vitro* experiment (Grauer et al.1997), **Figure 3B.**

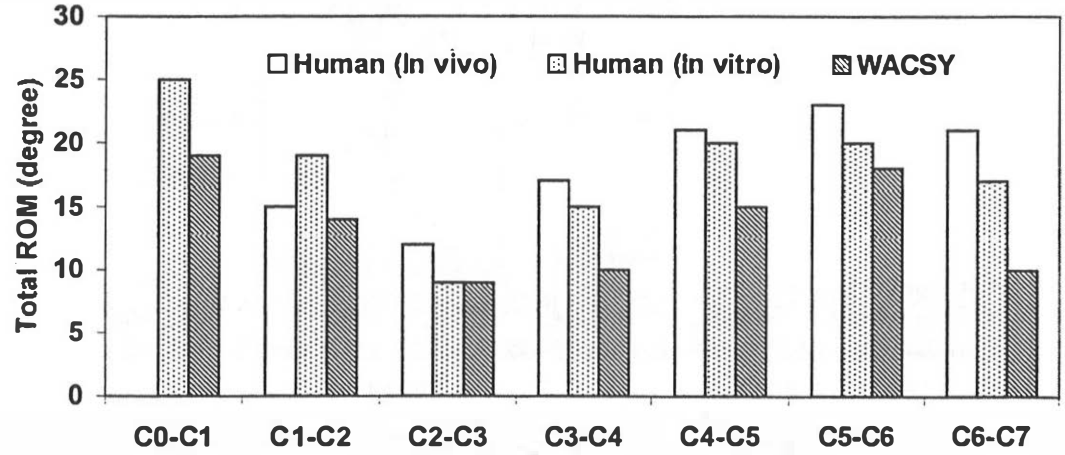


Figure 3A. Static comparison of *in vitro, in vivo* and WACSY.

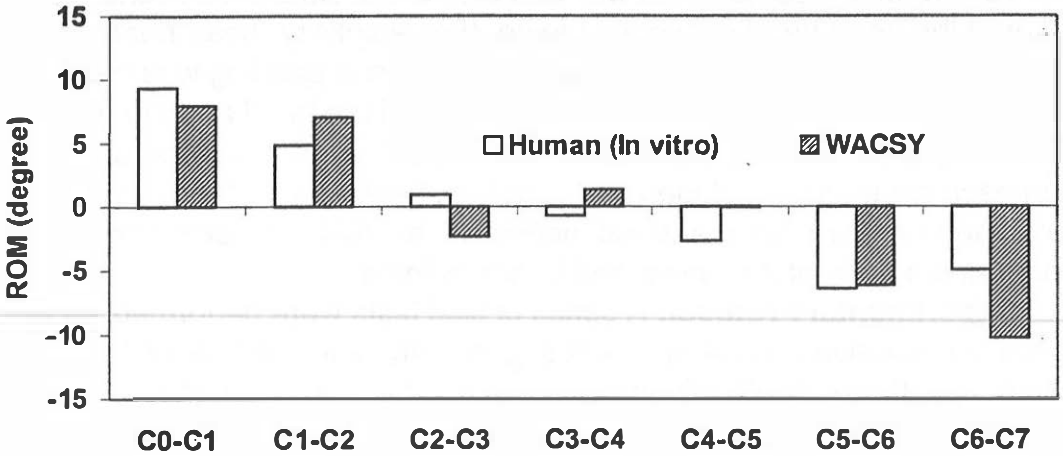


Figure 3B. Dynamic comparison of *in vitro* and WACSY.

THE EXPERIMENTS:

The Apparatus: Whiplash trauma was simulated by using the test sled apparatus shown in **Figure 4.** The WACSY model was mounted on the trauma sled, which slides on linear bearings. A 5.5 kg head surrogate with appropriate moment of inertia (50th percentile male) was mounted on top of WACSY. Since this version of WACSY does not include simulated muscles, the head weight was supported with a pneumatic suspension system, which counteracted the gravitation load on the head, but did not constrain the physiological spinal motions during the whiplash trauma. The sled springs were compressed by the pneumatic piston to a pre-determined force, corresponding to a pre-determined sled acceleration. On command from the computer, the springs were released and the impactor impacted the sled to accelerate. As the T1 vertebra of WACSY was rigidly attached to the sled, the acceleration of the T1 and sled were identical.

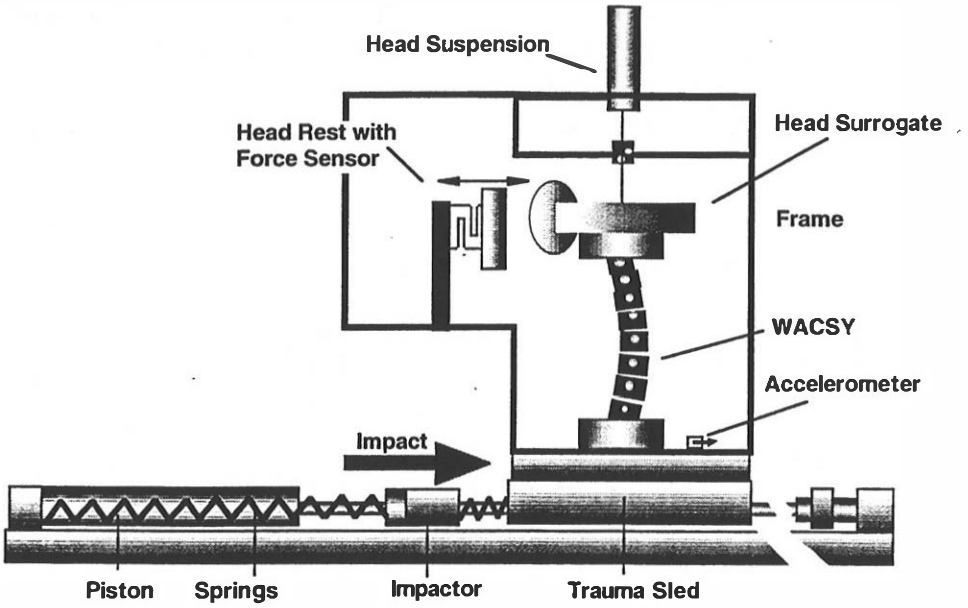
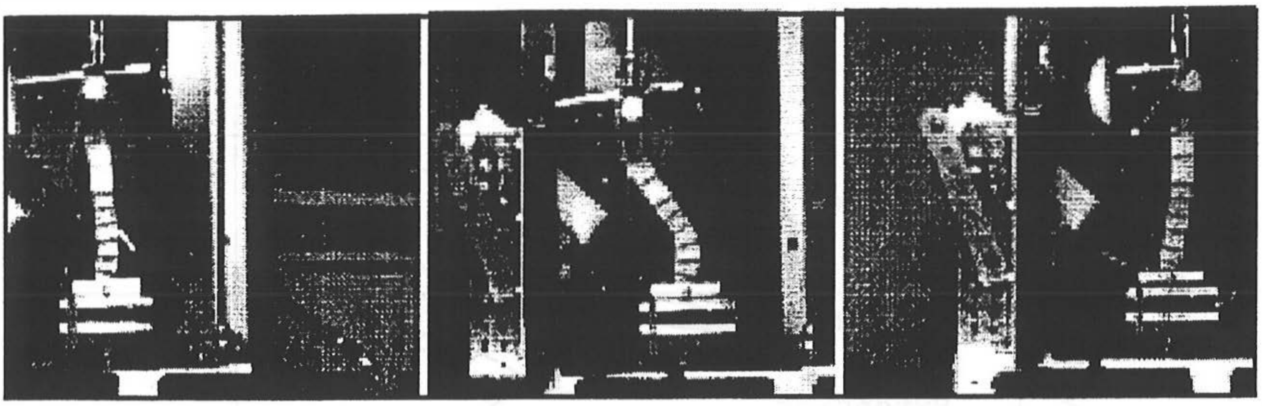


Figure 4. The Sled with the WACSY in place.

An instrumented headrest was attached to the sled, which continuously measured the head-headrest contact force. (For simplicity "head-headrest" is shortened to "headrest".) The stiffness of the headrest padding was measured to be 24 N/mm. The initial gap between the back of the head and the headrest could be adjusted in 2cm increments to a maximum of 10 cm. Measurements during each experiment included: sled position, head motion (horizontal, vertical, and rotation), intervertebral motions of the WACSY, forces and moment at the base of the spine, and headrest force.

Experimental Protocol: A series of sled tests were performed, where the sled acceleration and initial headrest gap were varied. A total of 12 experiments: three accelerations (2, 4, 8 g) and four headrest gaps (2, 4, 6, 10 cm), were investigated. A few high speed video frames from a trauma run show the WACSY in action, **Figure 5**.



0 ms 50 ms 100 ms

Figure 5. High Speed-movie of WACSY during whiplash trauma.

RESULTS:

A REPRESENTATIVE EXAMPLE:

The results from each of the 12 whiplash simulations were first interpreted in the time domain. A representative example due to impact acceleration of 8g and an initial headrest gap of 2cm, is first presented. For the sake of clarity the data has been truncated beyond the point at which the headrest force reaches its highest value. The intervertebral motion is shown in **Figure 6**, where flexion is positive and extension is negative. As shown the lower joints are predominantly in flexion, and the higher joints are mostly in extension. This behavior indicates an "S" shape to the spine which has been observed *in vivo* (Ono et al.1998) and *in vitro* (Grauer et al.1997). The IV-NIC, corresponding to the intervertebral motions, was computed by dividing the values in **Figure 6** by the corresponding $\theta_{physiological}$ values shown in **Figure 1**.

IV-NIC is compared to NIC in **Figure 7**. There are several points to note. The IV-NIC for this run (8g acceleration and 2cm headrest gap) shows that the potential for injury is highest at C6 - C7 level (IV-NIC = 2.25) and that the injury at this level will be caused due to extension of the spine. Further, there is also risk for injury to a lesser degree at C1 - C2 (IV-NIC = 1.5), and the injury is caused by flexion of the spine at this level. In contrast, the normalized NIC value of 1.5, i.e. NIC = 22.5, indicates only the magnitude of the potential injury. Thus, IV-NIC provides a more comprehensive information about the neck injury.

THE TWELVE RUNS:

A comparison of the two injury criteria for various headrest gaps and impact accelerations is shown in **Figure 8**. The IV-NIC values are shown along with the injury mode of extension (E) and flexion (F), Figure 8A. The NIC values are shown in Figure 8B. In general both the NIC and IV-NIC increased with increasing impact acceleration, but the IV-NIC provided additional information concerning the mode of potential injury and the site of injury (not shown). Interestingly, somewhat higher values of both injury criteria occurred at intermediate headrest gaps of 4 and 6 cm. If future experiments validate these observations, then this information may be helpful to the designer of specific whiplash prevention devices.

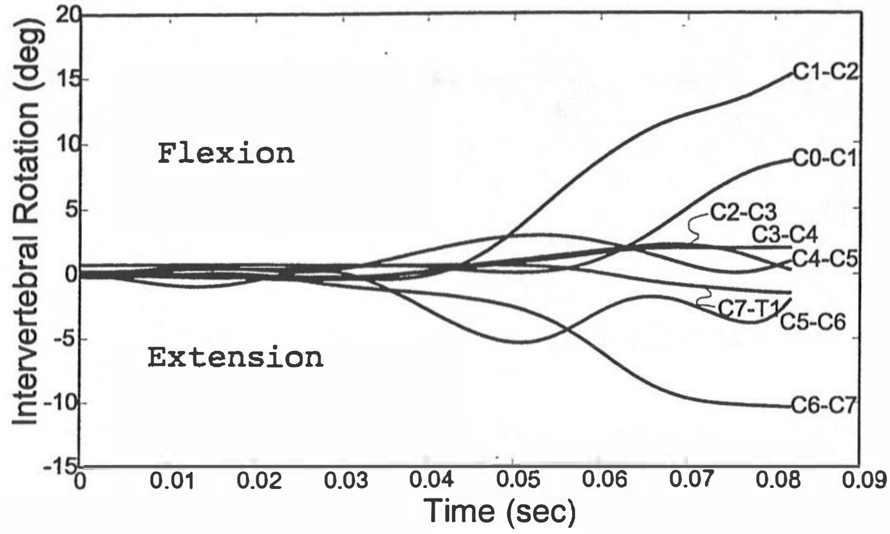


Figure 6. Intervertebral rotaion w.r.t. time (8 g acc. and 2 cm gap).

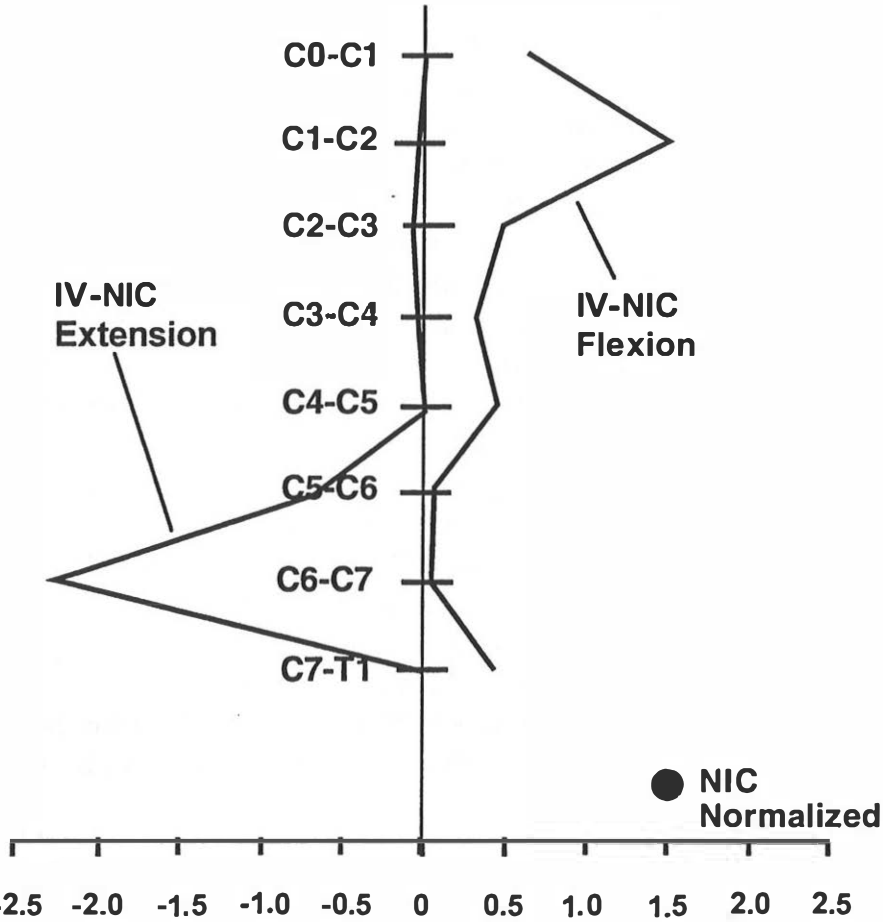


Figure 7. IV-NIC at each intervertebral joint in flexion and extension, and the NIC value. The maximum values of IV-NIC and NIC occurred at 82 ms. Experimental runs for sled acceleration of 8g and headrest gap of 2cm.

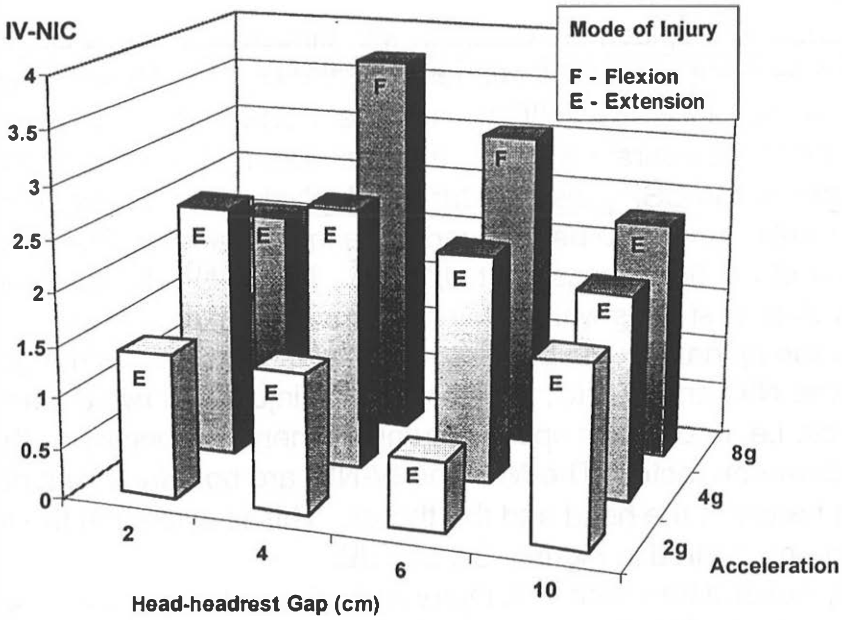


Figure 8A. IV-NIC for all 12 runs using WACSY

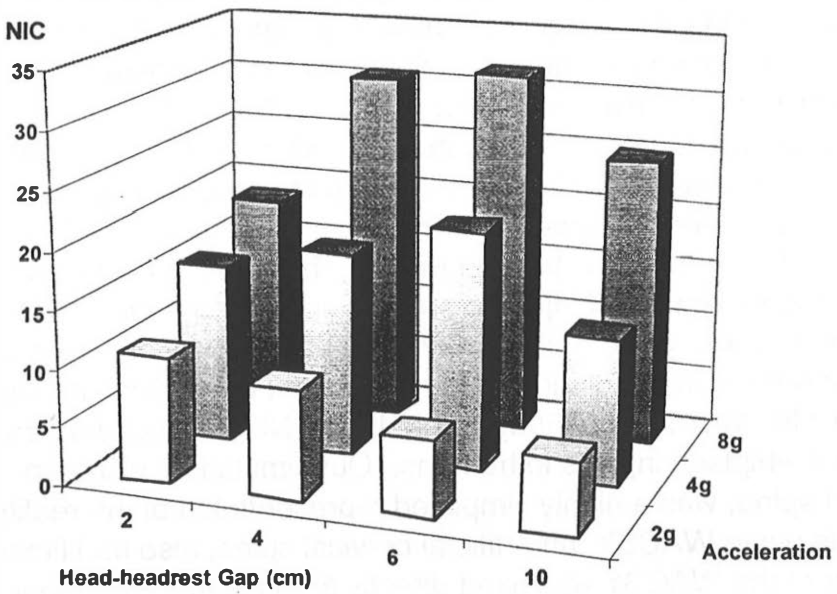


Figure 8B. NIC for all 12 runs using WACSY.

DISCUSSION

A neck injury criterion documents the occurrence of neck injury. A validated neck injury criterion is an important design tool for the evaluation and improvement of existing injury prevention systems and for the testing of new designs. In spite of injury prevention systems, the neck injuries do occur. As most injuries in whiplash are of soft tissues (AIS 1 level), they are difficult to detect even by modern imaging techniques such as MRI. The clinician/surgeon who treats a whiplash injured patient needs to know the probable location of the injury and the anatomic component most likely to have been injured. The neck injury criterion IV-NIC presented here has the potential to provide such detailed information, useful for the designer as well as for the clinician/surgeon.

The injuries of whiplash are complex with diffuse and varied clinical symptoms such as neck pain, neck stiffness, dizziness, etc. There could be several injury mechanisms. The NIC (Bostrom et al.1996) is based upon the hypothesis that it is the neural elements, e. g. ganglia, that are injured due to dynamic changes in the CSF pressure during whiplash. The intervertebral discs and ligaments, have also been found to be injured after whiplash-type traumas (Hamer et al.1993, Jonsson et al.1994). The IV-NIC is based upon results of such clinical studies which have documented injuries to several components of the spinal column because of whiplash trauma. Although the two injury criteria: NIC and IV-NIC, are based upon injuries to two different parts of the neck, i.e. neural and spinal column elements respectively, there is an underlying common factor. The NIC and IV-NIC are both functions of the relative motion between the head and the thorax. This is evident in the results of our simulation presented in Figures 8A and 8B.

Recently several new whiplash injury reduction systems have been incorporated into cars. These systems are based upon the concept that reducing head motion relative to the thorax will reduce the neck injuries. Thus we designed our simulated whiplash experiments in which the head-headrest gap was altered. We found a complex nonlinear relation between the headrest gap and potential injury as defined by both IV-NIC and NIC. The study also showed the additional features of IV-NIC in comparison to NIC. For example, in addition to the documentation of the occurrence of potential injury, the IV-NIC was able to determine the location of the injury on the spine and whether the injury occurred in flexion or extension mode. This latter aspect is important as it may lead to identification of injury to specific spinal component, e.g. facet joints. Such detailed injury information may be used to significant advantage by the clinician/surgeon in the diagnosis and treatment of whiplash injuries.

The major limitation of the study is that the IV-NIC has not yet been correlated to real whiplash injuries in humans. Our simulation, using an artificial cervical spine, was a highly simplified representation of the reality. The experiments using WACSY, an artificial cervical spine, also had limitations. The T1 vertebra of the WACSY was fixed directly to the sled. This is not physiological as volunteer experiments have shown that the T1 vertebra moves during whiplash. What effect this motion would have on NIC and IV-NIC, is presently not known. Future human cadaveric and human volunteer studies may provide some validation for the IV-NIC.

CONCLUSION

A new neck injury criterion IV-NIC for whiplash is presented. It is based on the hypothesis that neck injuries occur when an intervertebral motions during whiplash exceeds the physiological limit. This criterion has the advantage that it provides comprehensive information about the neck injury and injury mechanism. Such information may be valuable to the designers of whiplash injury prevention systems, and to the clinician/surgeon for the improved diagnosis and treatment of these soft tissue injuries. Future research is needed to correlate IV-NIC with actual human neck injuries.

Acknowledgements: This research was funded in part by Volvo Research Foundation, Volvo Educational Foundation and Dr. Pehr Gyllenhammar Research Foundation.

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