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Computer Modeling of Trans-Shoulder Forces In Motor Vehicle Accidents

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ABSTRACT

It is hypothesized that undiagnosed shoulder instability is a major contributor to "whiplash syndrome". The energetics of low to moderate speed rear end collisions were investigated to see if shoulder forces were sufficient to cause structural damage to the glenohumeral ligaments by computer simulation of 10, 15, 20, 25, 30, and 35 mph rear end collisions. Forces at the shoulder can easily exceed 400 lbs in collisions over 20 mph. Results of modeling indicate that injuries about the shoulder girdle, including complex instability, should be anticipated following low to moderate speed automobile collisions. Instability associated with MVA's differs both in magnitude and mechanism from the more common sports associated shoulder instability.

INTRODUCTION

Motor vehicle accidents commonly result in long term disability and suffering. Improved engineering has led to decreased mortality rates over the last 30 years but has increased the frequency of long term disabilities. Hohl, in 1974, noted that 40% of patients in his practice continued to receive treatment up to 10 years after sustaining "whiplash" injuries. [5] The National Transportation Safety Board web site estimates that fifty per cent of individuals injured in a motor vehicle accident have sequelae. The mechanism of injury is commonly described as whiplash, while cervical spine injuries are cited as the major physical injury.[6,11,19,20] The resulting symptoms have been characterized as the cervical-brachial syndrome, whiplash syndrome, or upper cervical syndrome. The components include, headache, neck pain, vertigo, facial paresthesia, shoulder pain and diffuse weakness, sensory loss and pain in one or both upper extremities. [12] These symptoms are invariably ascribed to a vague and nonspecific soft tissue injury of the neck and cervical spine for the initial few months and then converted to a psychiatric diagnosis if normal function does not return in several months. Occasionally, the individual sustains a cervical spine fracture or ruptured disc, or is diagnosed with a thoracic outlet syndrome and is successfully treated for this condition. [1, 8, 9, 23] Most individuals with these symptoms never receive a specific diagnosis and treatment remains palliative and ongoing. [10]

Several authors have reported acute MRI results that show rare injury to the cervical spine. [4, 13, 14, 15, 18] This author noted an almost universal occurrence of shoulder instability in a consecutive series of chronic whiplash patients. Treatment of the shoulder instability resulted in excellent symptom resolution. Of note, the patterns of intra-articular injury found at surgery were significantly different from those found in the more widely described sports associated dislocations. Irwin et al. reported a high incidence of shoulder injury in a set of low speed side impact experiments at Wayne State University. [7] Computer-assisted crash modeling was performed to advance our understanding of the mechanism and forces generated across the shoulder during low to moderate rear end collisions. Collision modeling was performed using Dynaman (GESAC, In. West Virginia) version 2.51.14.

MATERIALS AND METHODS

Dynaman is a crash modeling program that incrementally calculates the forces and accelerations of planes and volumes to analyze the results of collisions on vehicles and passengers. The modeling process includes, modeling the vehicle acceleration, developing a model of the interior of the motor vehicle, placing a modeled passenger in the vehicle and performing the simulated collisions. The Dynaman program was used to model 10, 15, 20, 25, 30 and 35 miles per hour rear end collisions. Upper and lower bound of collision energetics were manipulated by changing the imparted acceleration curves from 100% change in velocity (elastic condition) to 50% change in velocity. The 50% value corresponded to observed velocity changes seen in impact testing with 60% energy losses and equal masses in the bullet and target vehicles. [22] The elastic condition would be the upper bound of a larger vehicle striking a smaller vehicle. Triangular acceleration impulses with a duration of 110 msec and appropriate velocity changes were used to model the acceleration of the target vehicle passenger compartment. An adult male passenger was modeled based on the Hybrid III crash dummy. The starting position for the passenger was seated facing forward, hands at the sides, wearing a lap belt and shoulder harness (three-point restraint). Appropriate body segments were identified to allow calculation of the forces across the shoulder joint during the simulation. The shoulder joint was modeled as an unconstrained ball and socket joint ("Free Joint" in Dynaman terminology). The forces modeled included: force in the restraint system, forces at the interior surfaces of the passenger compartment, and forces affecting the head, neck, torso and extremities. The initial process was aimed at determining the forces and accelerations sustained by the human body in a natural starting position with the torso positioned in a neutral sitting state with no rotation and the arms resting at the side. The initial impact was square to the longitudinal axis of the vehicle. Three-point restraints were simulated, again, in the ideal position. The forces and accelerations due to interior vehicle surfaces, including the seat, cab and restraint system, were computed. The forces and accelerations of the shoulder were also computed. Total acceleration of the vehicle and passengers were computed. Each velocity was tested with four seat types, default, stiff, soft and cushion. Figure 1.

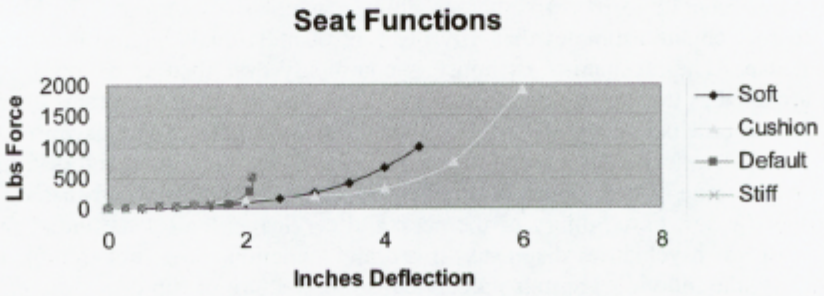

Figure 1: Seat Back Force Deflection Functions

RESULTS

Peak accelerations on the vehicle and total body were less than 30 G's in all cases. Forces were calculated in pounds (lbs.) and accelerations in gravity's (G's). Table 1 summarizes the magnitude of the peak forces seen for the various conditions. Peak forces occurred between 80 and 100 msec from the beginning of the collision and exceeded 100 lbs for all conditions above 15 mph.

Table 1. Force Magnitude Summary

Impact Speed	60% Energy Loss	Elastic
10 mph	50	78
15 mph	110	290
20 mph	135	705
25 mph	150	710
30 mph	400	760
35 mph	460	850

Forces are in pounds

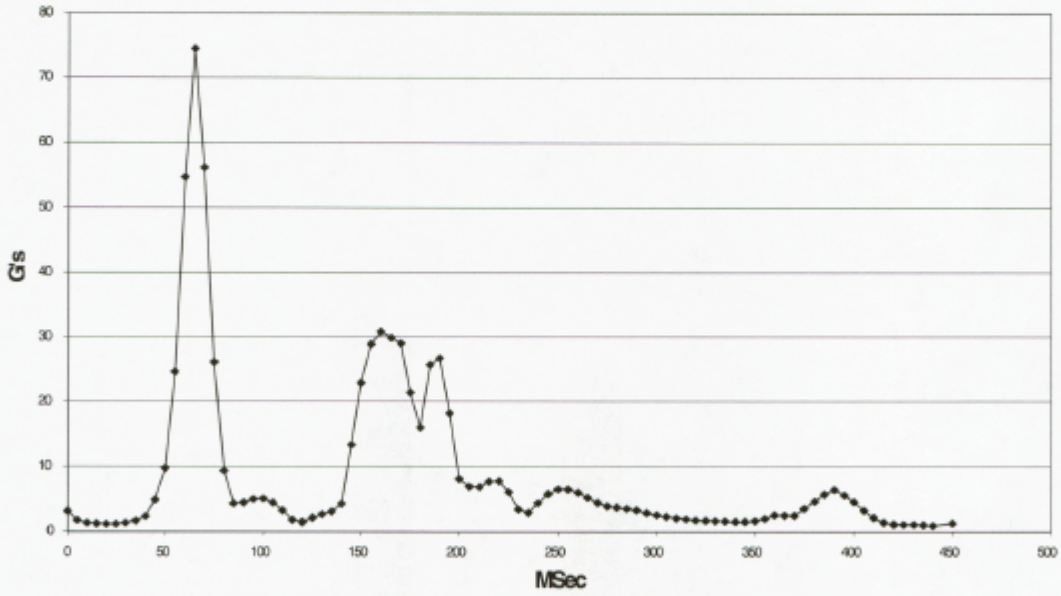

Figure 2: Head Acceleration 35mph Rear End Collision 60% Energy Loss

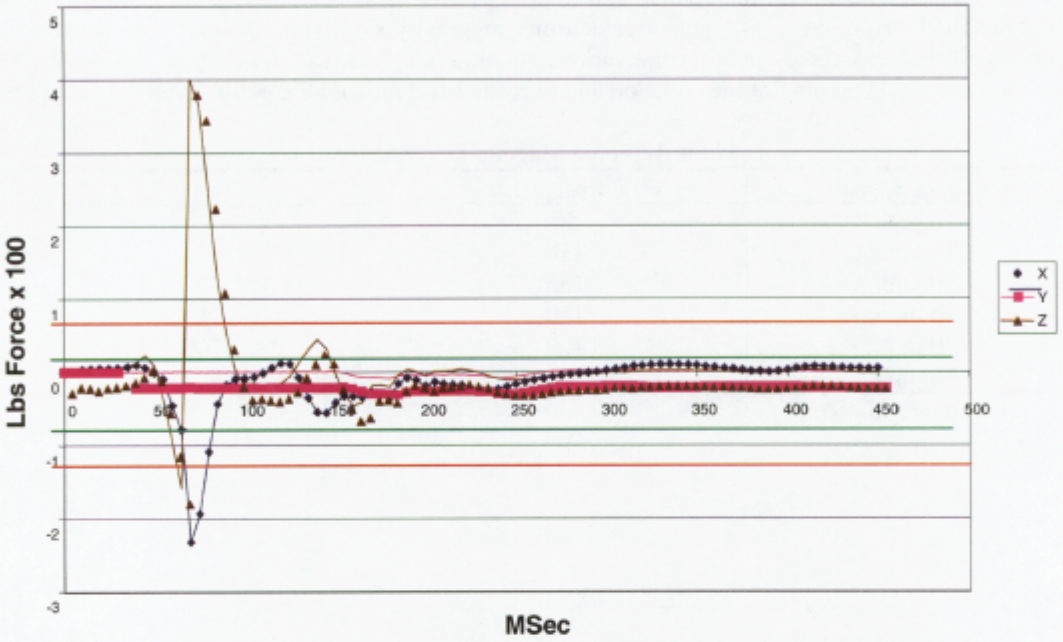

Figure 3: Shoulder Forces 35mph Rear End Collision 60% Energy Loss

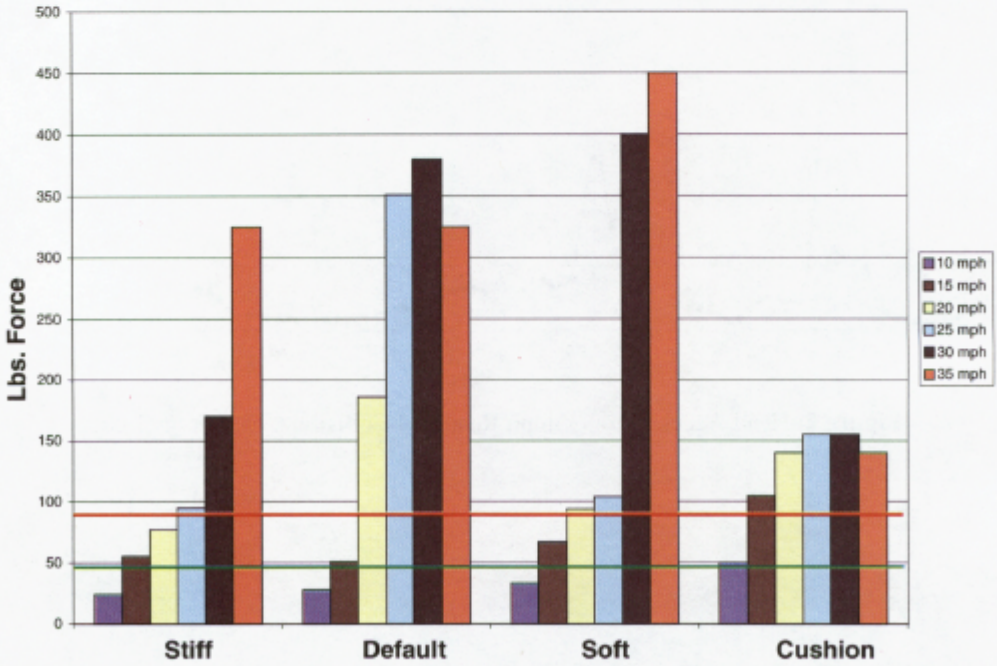

Figure 4: Shoulder Forces by Velocity and Seat Type

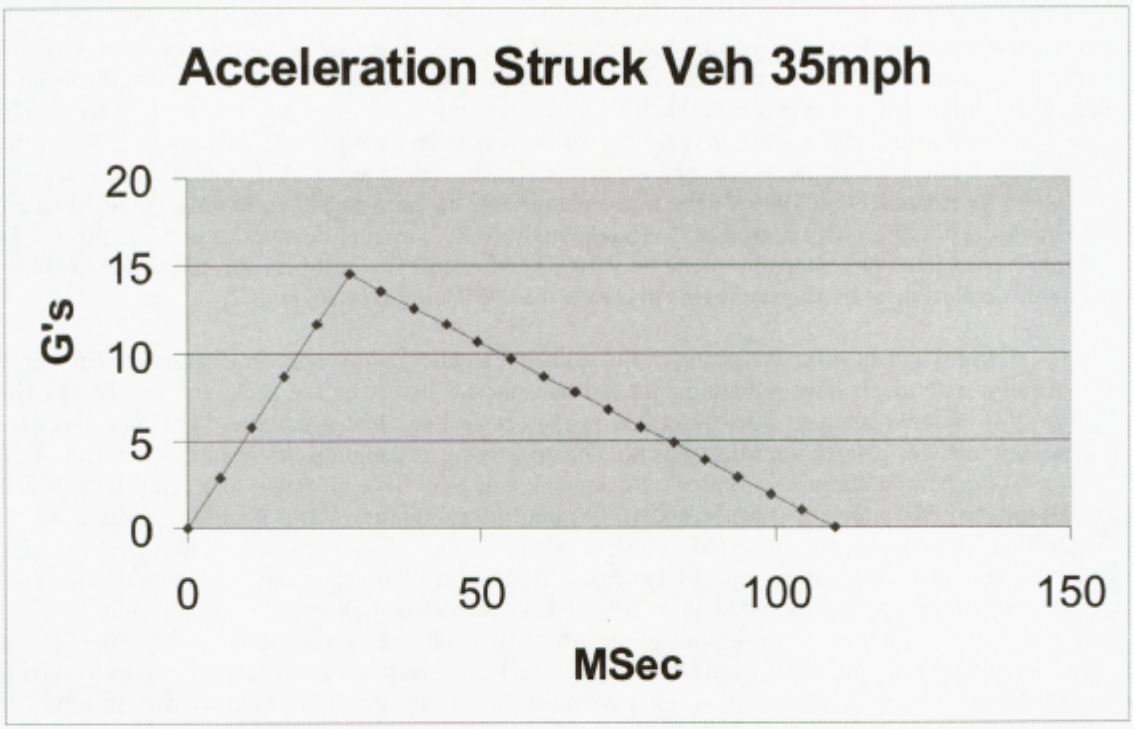

Figure 5: Acceleration Profile of Struck Vehicle 60% Energy Loss

Particularly interesting is the pattern of force curves generated about the head, neck and upper extremities. The head and neck are exposed to two large accelerations. The first occurs as the head and neck are driven back into the seat and the second occurs after the body rebounds off of the back of the seat into the restraint system. The shoulder receives a large posterior impulse at the same time the forces in the inferior and superior directions go through a large oscillation, first in the superior direction and then in the inferior direction. The forces become large enough at about 30 mph that near simultaneous anterior, posterior and inferior shoulder instability should be anticipated. The energy of the axial portions of the body is absorbed in a controlled fashion by the restraint system. This is contrasted with the extremities in which the energy resident in the limbs must be absorbed by the joints or by impact with portions of the cab.

DISCUSSION

Chronic pain and disability frequently occur after moderate speed motor vehicle accidents. [5, 10, 12, 16, 19, 21, 23,] NTHSA estimates that approximately 6 million MVA's occur each year in the United States resulting in just over 40,000 deaths. Improved automotive designs have led to major reductions in mortality rates during the last thirty years. The improved survivability has created the impression that these injuries are minor and that they are not caused by significant forces. Several studies during the last thirty years have demonstrated 20% to 80% chronic injury rates following whiplash injury. [5, 15, 16, 17, 21] These injuries have generally been ascribed to soft tissue injuries about the cervical spine. Wickstrom and others demonstrated the types of cervical spine injuries that occur in acceleration-deceleration injuries using a monkey model. [24] Certainly, cervical spine injuries are major life

threatening events that occur during motor vehicle accidents. Fortunately, improvements in automotive design and restraint systems have resulted in major reductions in this catastrophic injury. Although the magnitude and numbers of cervical injuries have been reduced, long term dysfunction and pain continues to be a major problem. The chronic whiplash syndrome has been exceptionally resistant to medical management, largely due to the vague and nonspecific nature of the diagnosis, "soft tissue" injury of the neck. Several recent studies, including acute MRI studies (first week post collision) by Ronnen et al; 1996 [18] have found identifiable cervical pathology in only 1% of 100 cases in patients with whiplash syndrome. [18] Alger's study of 20 consecutive anterior cervical fusions for whiplash associated radiculopathy found only 10% good results .[1] Treatment for most other causes of ruptured cervical discs by surgery results in greater than 90% improvement rates.

Careful and specific evaluation of the neck and shoulder allow specific anatomic diagnosis. [11] Frequently, individuals have radiating pain and paresthesias involving the neck, arm and hand. This group of symptoms has also been described as the cervical-brachial syndrome. The pain described invariably includes painful trapezius spasm. The underlying assumption has been that the neck is the source of the painful stimulus. Matsen , Rockwood, and Neer have all found that complaints of pain localized to the superior shoulder are frequently associated with shoulder pathology. [11] Understandably, treatments directed at the cervical origins of pain in this syndrome have been unsuccessful in a large proportion of patients. Radanov (1996) in a masterful cataloging of the whiplash symptom complex noted that 53% of his patients had shoulder problems and 35% had thoracic outlet syndrome [16]. Resistance of the whiplash syndrome to treatments aimed at the cervical spine, combined with the negative MRI findings and other subjective and objective findings led him to conclude that whiplash syndrome is not psychiatric in origin nor is it primarily a neck injury [17]. However, Radanov did find that psychometric measures were consistent with persistent injury.

This author noted an unusual pattern of shoulder instability in patients complaining of cervical brachial pain following motor vehicle accidents. This included unilateral unidirectional, bilateral unidirectional, unilateral multidirectional and bilateral multidirectional instability. Virtually all combinations of anterior, inferior and posterior instability were present in all of the chronic whiplash patients examined over the last several years. Anatomic findings were also exceptionally interesting, with high incidence of multiple injuries to the glenohumeral ligaments. The core symptoms of the chronic whiplash syndrome then take on new meaning. This mechanism of injury creates exceptionally large forces and consequently large displacement dislocations around the shoulder girdle. This includes the sterno-clavicular joint. Ticker, et al; described the mechanical characteristics of the glenohumeral ligaments which are consistent with failure of the ligaments at stresses between 50 and 100 lbs.[2]

Computerized modeling demonstrated the large magnitude of forces affecting the shoulder in MVA. The magnitude and direction of forces crossing the shoulder would lead one to expect a complex set of injuries involving the scapula, clavicle, rotator cuff, and the anterior posterior ligaments of the shoulder. Key characteristics of the forces involving the shoulder are the magnitude and indirect nature of the force generation. Numerous case reports have cited brachioplexus avulsions, acute shoulder dislocation, rotator cuff tears, dislocations and fractures of the clavicle, and upper extremity fractures in patients following MVA. Historically, this group of injuries is also associated with poor treatment responses. The magnitude of the forces directed at the upper extremity in moderate collisions account for the observed injuries and predicts multiple injuries following MVA. Recognition and treatment of the described injuries should improve rates of long term disability and suffering following MVA.

The neck forces modeled in this study correlate well with crash testing data, and exceed shoulder force below 30 mph. In fact, the neck forces remain very constant over the tested range

while the shoulder forces increase four fold. This probably represents the result of safety engineering over the last 40 years.

Rear end unanticipated collisions have the highest rate of chronic whiplash syndrome. There are several factors that contribute to this occurrence. The forces on the shoulder occur over a 100 msec interval that doesn't allow reflex tightening of the shoulder girdle muscles; therefore, the ligaments are unsupported dynamically. Second, guarding locks the passenger to the vehicle and the "whiplash" doesn't occur because the body is exposed to accelerations that are closer to the vehicle acceleration.

CONCLUSIONS

Injuries about the shoulder girdle, including complex instability, should be anticipated following low to moderate speed automobile collisions. These injuries may include all of the structures of the upper extremity. Instability associated with MVA's differs both in magnitude and mechanism form the more familiar sports associated shoulder instability. Studies directed toward the complete classification of upper extremity injuries associated with MVA's should significantly improve the treatment results in this common injury. More complete modeling and crash testing needs to be performed to define the complete range of energy transfer into the upper extremities.

REFERENCES

1. Algers G, Pettersson K, Hidingsson C, et al: Surgery for chronic symptoms after whiplash injury. Follow-up of 20 cases. Acta Orthop Scand 64(6):654-656, 1993.

2. Bigliani LU, Pollock RG, Soslowsky LJ, et al: Tensile properties of the inferior glenohumeral ligament. J Orthop Res 10:187-197, 1992.

3. Capp JP, Obermeyer JA: A comparison of frontal and side impact: crash dynamics, countermeasures and subsystem tests. Proc of the 35th Stapp Car Crash Conf. Nov 1991.

4. Hagstrom Y, Carlsson J: Prolonged functional impairments after whiplash injury. Scand J Rehab Med 28(3):139-146, 1996.

5. Hohl, Mason: Soft-tissue injuries of the neck in automobile accidents. J Bone Joint Surg 56A:1675-1682, 1974.

6. Horsch JD, Melvin JW, Viano DC: Thoracic injury assessment of belt restraint systems based on Hybrid III chest compression. Proc of the 35th Stapp Car Crash Conf. Nov 1991.

7. Irwin AL, Walilko TJ, Cavanaugh JM, et al: Displacement responses of the shoulder and thorax in lateral sled impacts. 37th Stapp Car Crash Conference Proceedings SAE Tech Doc 933124 165-173, 1993.

8. Jonsson H, Cesarini K, Sahlstedt B, et al: Findings and outcome in whiplash-type neck distortions. Spine 19(24):2733-2743.

9. Karlsborg M, Smed A, Jespersen H, et al: A prospective study of 39 patients with whiplash injury. Acta Neurol Scand 95(2): 65-72, 1997.

10. McKenzie JA, Williams JF: The dynamic behaviour of the head ans cervical spine during "whiplash". J Biom 4:477-490, 1971.

11. Neer CS: Dislocations. Shoulder Reconstruction. Philadelphia, W.B. Saunders Company 293-295, 1990.

12. Norris SH, Watt I: The prognosis of neck injuries resulting from rear-end collisions. J Bone Joint Surg 55B:608-611, 1983.

13. Pettersson K, Hildingsson C, Toolanen G, et al: MRI and neurology in acute whiplash trauma. No correlation in prospective examination of 39 cases. Acta Orthop Scand 65(5):525-528, 1994.

14. Radanov BP, Begre S, Sturzenegger M, et al: Course of psychological variables in whiplash injury a 2 year follow-up with age, gender and education pair-matched patients. Pain 64(3): 429-434, 1996.

15. Radanov BP, Sturzenegger M: Predicting recovery from common whiplash. Eur Neurol 36(1): 48-51, 1996.

16. Radanov BP, Sturzenegger M, DiStafano G: Long-term outcome after whiplash injury. A 2-year follow-up considering features of injury mechanism and somatic, radiologic, and ppsychosocial findings. Med-Baltimore. 74(5):281-297, 1995.

17. Radanov BP, Sturzenegger M, DiStefano G, et al: Relationship between early somatic, radiological, cognitive and psychosocial findings and outcome during a one_year follow_up in 117 patients suffering from common whiplash. Br J Rheum 33(5): 442-448, 1994.

18. Ronnen HR, deKorte PJ, Brink PR, et al: Acute whiplash injury: is there a role for MR imaging? A prospective study of 100 patients. Radiology 201(1):93-96, 1996.

19. States JD, Korn M, Massengill JB: The enigma of whiplash injury. NY State J Med 70(24): 2971-2978, 1970.

20. Sturzeneggar M, DiStefano G, Bogdan, et al: Presenting symptoms and signs after whiplash injury: the influence of accident mechanisms. Neur 44: 688-693, 1994.

21. Sturzenegger M, Radanov BP, DiStefano G: The effect of accident mechanisms and initial findings on the long-term course of whiplash injury. J Neurol 242(7):443-449, 1995.

22. Szabo TJ, Welcher J: Dynamics of low speed crash tests with energy absorbing bumpers. SAE Trans 101(6):1-8 Doc# 921573, 1992.

23. Voyvodic F, Dolinis J, Moore VM, et al: MRI of car occupants with whiplash injury. Neurorad 39(1): 35-40, 1997.

24. Wickstrom JK, Martines JL, Rodriquez R: Cervical sprain syndrome, experimental acceleration injuries of the head and neck. Proc Prev of Highway Accidents Symp. U of Mich. 182-187, 1967.