
Analysis of Human Test Subject Kinematic Responses to Low Velocity Rear End Impacts

**Whitman E. McConnell, Richard P. Howard, Herbert M. Guzman, John B. Bomar,
James H. Raddin, James V. Benedict, Harry L. Smith, and Charles P. Hatsell**
Biodynamic Research Corp.

**Reprinted from: Vehicle and Occupant Kinematics:
Simulation and Modeling
(SP-975)**

SAE *The Engineering Society
For Advancing Mobility
Land Sea Air and Space®*
INTERNATIONAL

**International Congress and Exposition
Detroit, Michigan
March 1-5, 1993**

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel:(412)776-4841 Fax:(412)776-5760

The appearance of the ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay a \$5.00 per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 27 Congress St., Salem, MA 01970 for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group



GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the SAE Global Mobility Database.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191

Copyright 1993 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Activity Board, SAE.

Printed in USA

90-1203B/PG

Analysis of Human Test Subject Kinematic Responses to Low Velocity Rear End Impacts

Whitman E. McConnell, Richard P. Howard, Herbert M. Guzman, John B. Bomar,
James H. Raddin, James V. Benedict, Harry L. Smith, and Charles P. Hattell
Biodynamic Research Corp.

ABSTRACT

The head, neck and trunk kinematic responses of four volunteer test subjects, recorded during a series of experimental low velocity motor vehicle collisions, have been measured and analyzed. Using data obtained from multiple high speed film, video and electronic accelerometer measurements of the test subjects, it was found that the actual kinematic responses of the human head, neck and trunk that occur during low velocity rearend collisions are more complex than previously thought. Our findings indicate that the time-honored description of the cervical "whiplash" response is both incomplete and inaccurate.

Although the classic "whiplash" neck response to rearend collisions and the widely accepted hyperextension/hyperflexion cervical injury mechanism have been extensively written and speculated about, there have been little human experimental data available, especially for low velocity collisions. Low velocity collisions are defined in this report as motor vehicle collisions in which the impact related change of the rearended vehicle's velocity (ΔV) is about 12.9 kph (8 mph) or less. Throughout nearly 4 decades of experimental crash testing, low velocity mishaps (as defined above) have been felt to have a minor injury causation potential and have remained a relatively unstudied area. The absence of good experimental data, accurately defining real occupant kinematic response during this common type of traffic accident has spawned a plethora of divergent concepts, ideas and speculation about possible injury mechanisms.

In February 1991, a series of vehicle collision tests using fully instrumented volunteer human test subject/drivers and a Hybrid III manikin passenger was conducted, utilizing local testing facilities. This project was undertaken to better define human, dummy and vehicle responses during low velocity collisions.

METHODS

VEHICLES — Four test vehicles, a 1986 Dodge 600 convertible, a 1984 Buick Regal Limited coupe, a 1984 Ford Club Wagon van and a 1984 GMC 1500 pickup truck were prepared for the test protocol. Each vehicle was without evidence of collision structural damage and was in roadworthy condition with factory standard equipment and parts. The convertible and coupe had factory standard energy absorber bumper systems, and the truck and van bumper systems were rigidly mounted to the vehicle frame structure. Although each vehicle remained in stock condition to the maximum extent possible, the testing protocol required a number of modifications. The test subjects had to be photographically accessible, so the upper portion of the Ford van's left B-pillar and the front doors of each vehicle were removed. The rear window of the pickup truck was replaced with a small Lexan panel, and headrests in the convertible and the coupe were kept in the raised position. Several mounting points for high speed cameras were installed on each vehicle. Each vehicle's original, factory standard 3-point restraint system was used throughout the tests. Vehicles were checked prior to testing and any bumper assembly damage found was repaired with new parts.

TEST SUBJECTS — The proposed test protocol was evaluated by the University of Texas Health Science Center Institutional Review Board and IRB Protocol #9010099006 of the University of Texas Health Science Center, under DHHS Regulation 46.110(3), approved the use of four human test subjects selected from the staff of Biodynamic Research Corporation in the test series. Four healthy volunteer male test subjects, ranging in age from 45 to 56, completed pre-testing physical evaluations including radiographic imaging studies of the cervical, thoracic and lumbar regions of their spines. Test subject marking for photographic analysis included a stiff "U" shaped yellow rod attached to an individually fitted biteblock and accelerometer assembly and oriented rearward on both sides parallel to the aluminum strip connecting the accelerometers and the closed

mandible/maxilla. There was also a photographically visible mark placed below and slightly behind the left external auditory canal over the mastoid prominence as an approximation of the lateral projection of the upper end of the cervical spine. Reference marks were applied to the skin over the test subject's left neck, simulating the lateral projection of the cervical spine. Targets were placed approximately over the left gleno-humeral joint and lateral left elbow on a tight fitting garment worn over the torso and arms. A Hybrid III anthropomorphic test dummy was fitted with a biteblock type accelerometer assembly and had similar right side anatomical reference point markings applied, with the exception of the dummy's already exposed neck area.

INSTRUMENTATION — Each vehicle, had a triaxial LSCB-10 accelerometer array mounted on the vehicle frame to measure Gx (forward/rearward), Gy (right and left lateral), and Gz (upward/downward) motions and a biaxial accelerometer array (Gx and Gz) on the driver's side seatback.

Contact switch operated flash units were installed in visible positions to allow photographic time marking of initial bumper to bumper contact and a similar contact switch cued the electronic data acquisition system. Additional instrumentation to accomplish other test objectives was also installed on the vehicles. Test subject instrumentation included a lightweight triaxial accelerometer assembly of Endevco #7290-30 and Endevco #7290-10 accelerometers mounted on a short aluminum strip fixed to an individually fabricated mouth piece (biteblock) which, when held with normal jaw closure pressure, allowed no appreciable relative motion between the accelerometer assembly and the test subject's maxilla/mandible. An identical accelerometer array mounted on an aluminum strip was affixed in an equivalent position on the Hybrid III manikin's head. A biaxial accelerometer assembly using similar sensors was affixed to a corset-like garment and was worn by one test subject during two of the test runs to measure Gx and Gz direction acceleration. Electronic data transfer during test runs was accomplished by a sliding loop umbilical bundle connected to a PAC-5800 high volume data acquisition system housed nearby.

PHOTOGRAPHIC EQUIPMENT — Photographic documentation of test runs was accomplished by several Redlake LoCam Model #51 high speed 16 mm cameras operated at 500 frames per second (nominal) and equipped with an LED timing light operating at 100 hertz. These cameras were mounted at various locations on the vehicles and from several fixed positions about the test site. One high speed video unit and several tripod mounted standard video cameras also recorded the events.

TEST SITE — The test site was established on a level section of a standard, asphalt paved roadway and had electronic speed trap instrumentation and high speed video tracking with near realtime velocity measurement capability. Impact speed reproducibility was achieved by the use of a specially constructed ramp permitting gravity acceleration of the striking vehicle. The striking vehicle's starting position on the ramp was calibrated before each test run to ensure that the resulting velocity at the impact point was in the desired range.

The actual closure speeds and resulting changes in velocity of both the striking and the struck vehicles during the test runs were accurately determined by high speed film, high speed video and the electronic speed trap with satisfactory agreement. High speed cameras on the vehicles and at fixed site positions were actuated by a central electronic control and the video cameras were controlled by individual operators responding to auditory and visual cues.

TEST PROCEDURES — Test runs were conducted according to a protocol which tested a variety of combinations of vehicle to vehicle collisions and exposed test subjects to both striking and struck roles during tests planned for a forward struck vehicle ΔV of 4 kph (2.5 mph) and 8 kph (5.0 mph). The striking vehicle was backed up the ramp by the test subject-driver to a calculated position and released with the transmission in neutral and the engine running. It then rolled down the ramp and through the impact point speed trap where the velocity was recorded. This procedure was repeated until the desired impact speed was reproducibly achieved. The vehicle to be struck was then placed into its stationary position at the impact point. The striking vehicle then rolled down the ramp and over the level pavement to the impact point. No vehicle control inputs were made during test runs, except for minimal steering inputs to ensure centerline contact between vehicles and late braking after the test impact perturbations were over. In some cases, to prevent an over or underide situation, the height of one of the two vehicles was elevated by the use of wooden planking which formed an elevated roadbed. After each test collision, the driver's physical condition was checked, post-test photographic assessment of vehicle damage was completed, and electronic test result data storage was accomplished. Data from ten manned vehicle to vehicle test collisions were recorded.

HEAD, NECK AND TRUNK KINEMATIC RESPONSE ANALYSIS — The purpose of this article is to report our findings after a detailed analysis of human head, neck and trunk kinematic responses occurring during and immediately after low velocity rear-end impacts. Relevant data included the recorded G-time information from the human and vehicle mounted accelerometers, displacement-time data taken from the high speed film record and the slow motion video record of each test subject's motion during the collision sequences. The electronic G measurement data was processed into a usable form with smoothing to eliminate noise artifacts and very short term transients. Biteblock G-time vector resultants were calculated from Gx, Gy and Gz data recorded for each collision sequence. In order to obtain true (earth orthogonal) G vector resultant data, mathematical coordinate transformation was done to account for the curvilinearly displaced path of the biteblock reference frame from its initial earth orthogonal orientation and required utilization of time-angle data obtained by measurement from the high speed film record. An additional series of mathematical manipulations gave an earth reference based G-time history for a point near the junction of the head and upper cervical spine. This information was correlated with point displacement information obtained from the high speed film by plotting each

test subject's reference points (biteblock, mastoid process, shoulder and hip) with respect to time, as well as the vehicle and background reference points using a precision optical digitizing process. Cervical extension and flexion angles were determined using digitized high speed film displacement data. The G-time and displacement-time data was then correlated and the results validated by a detailed comparison of the calculated data with the frame by frame video recordings of the impact related test subject kinematic responses.

RESULTS

TEST RELATED CLINICAL FINDINGS — Each test subject had from 3 to 7 vehicle to vehicle test collision exposures, divided between the striking and struck roles during the 10 test collision series. (See Table 1.) These test runs were conducted during two weekend test periods separated by an eight day hiatus. No test subject reported having discomfort symptoms during or immediately after any of the test collisions. Test subject number 4 noted no symptoms at all related to his 6 test exposures. Beginning

low and mid-neck discomfort over the area of his C6, C7 and T1 vertebra and discomfort in his trapezius musculature on the morning following his three test runs on day 10. The pain was gone the next day, but he continued to have mild discomfort on extreme neck extension and lateral flexion until it gradually resolved during the next three days. No treatment or therapy was needed and none of the test participants had any further symptoms that related to their test exposures for greater than eighteen months following the testing.

PHOTOGRAPHIC ANALYSIS OF AN EXAMPLE KINEMATIC RESPONSE — The following is a description of one test subject's kinematic responses to a typical test (Run 7), as he experienced a forward ΔV of 7.83 kph (4.87 mph). (See Figure 1.)

Phase 1 - Initial Response (0 to 100 milliseconds) —

During the first 50 milliseconds after bumper impact, the subject's entire body appeared motionless with reference to the test site background, while the vehicle and driver's seat moved forward about 5 to 8 centimeters (2 to 3 inches). At about 60 milliseconds after contact, the lower part of the seatback cushion had become compressed enough to begin moving the

Run No.	Test Subj No.	Struck Vehicle Type	ΔV (kph)	Test Subj No.	Striker Vehicle Type	ΔV (kph)	Day No.
1	2	Van	3.48	1	Convert	-4.81	1
2	1	Van	6.45	4	Pickup	-6.04	2
3	1	Pickup	3.04	4	Van	-3.35	2
4	4	Pickup	6.65	1	Van	-6.74	2
5	3	Convert	na	2	Coupe	na	10
6	3	Convert	8.06	2	Coupe	-7.82	10
7	2	Coupe	7.83	3	Convert	-9.24	10
8	2	Van	6.61	4	Pickup	-8.21	10
9	2	Coupe	3.93	4	Pickup	-3.28	11
10	4	Pickup	7.03	2	Van	-7.48	11

Table 1. Test Subject Driven Low Velocity Collision Test Series

about 45 to 60 minutes after Test 2, test subject number 1 reported a "twinge" of discomfort at the posterior base of his neck which lasted about two hours. The discomfort was gone by the time of his participation in test number 3 and did not recur later. Test subject number 2 noted the onset of "achiness" in the paraspinal musculature at the base of his neck the morning of test day 12, after participating in a total of 6 test runs during the preceding two day test period. His symptoms lasted about 4-5 hours and resolved without recurrence. Test subject number 3 reported the onset of mild

test subject's hips and low back forward and upward (See Figure 2). At the same time, the upper part of the seatback was flexing rearward with respect to the vehicle and the seatback cushion was being compressed on the test subject's still nearly stationary upper torso.

Phase 2 - Principal Forward Acceleration (100 to 200 milliseconds) — At about 100 milliseconds, the seatback had nearly reached its maximum rearward flexed position of about 10 degrees past its normal position, and the test subject's upper trunk had begun movement forward and upward. The

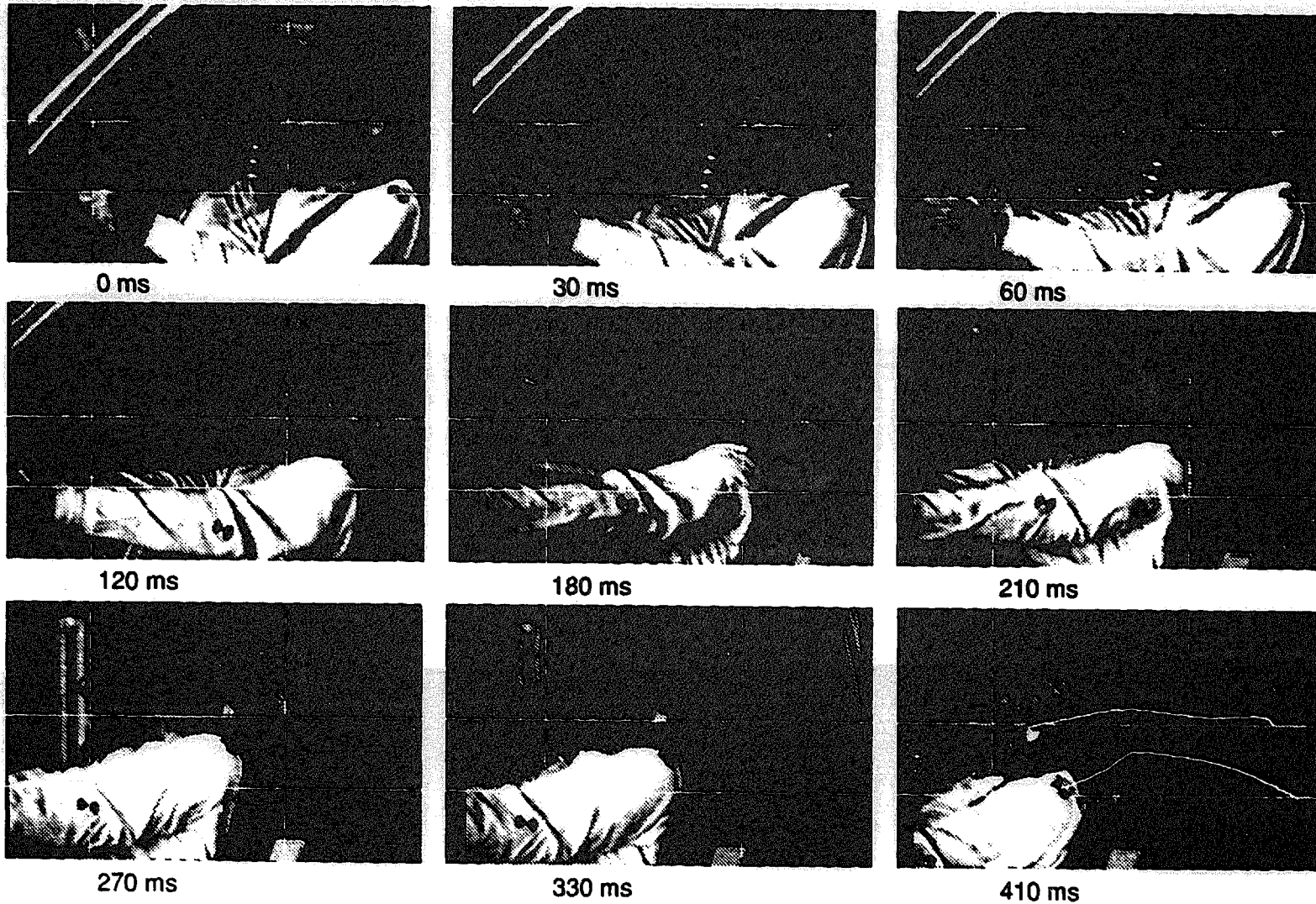


Figure 1. Example Response to Rear Impact - Test 7
Note. Grid lines are earth fixed. Last picture shows time trace of neck top and shoulder pathways.

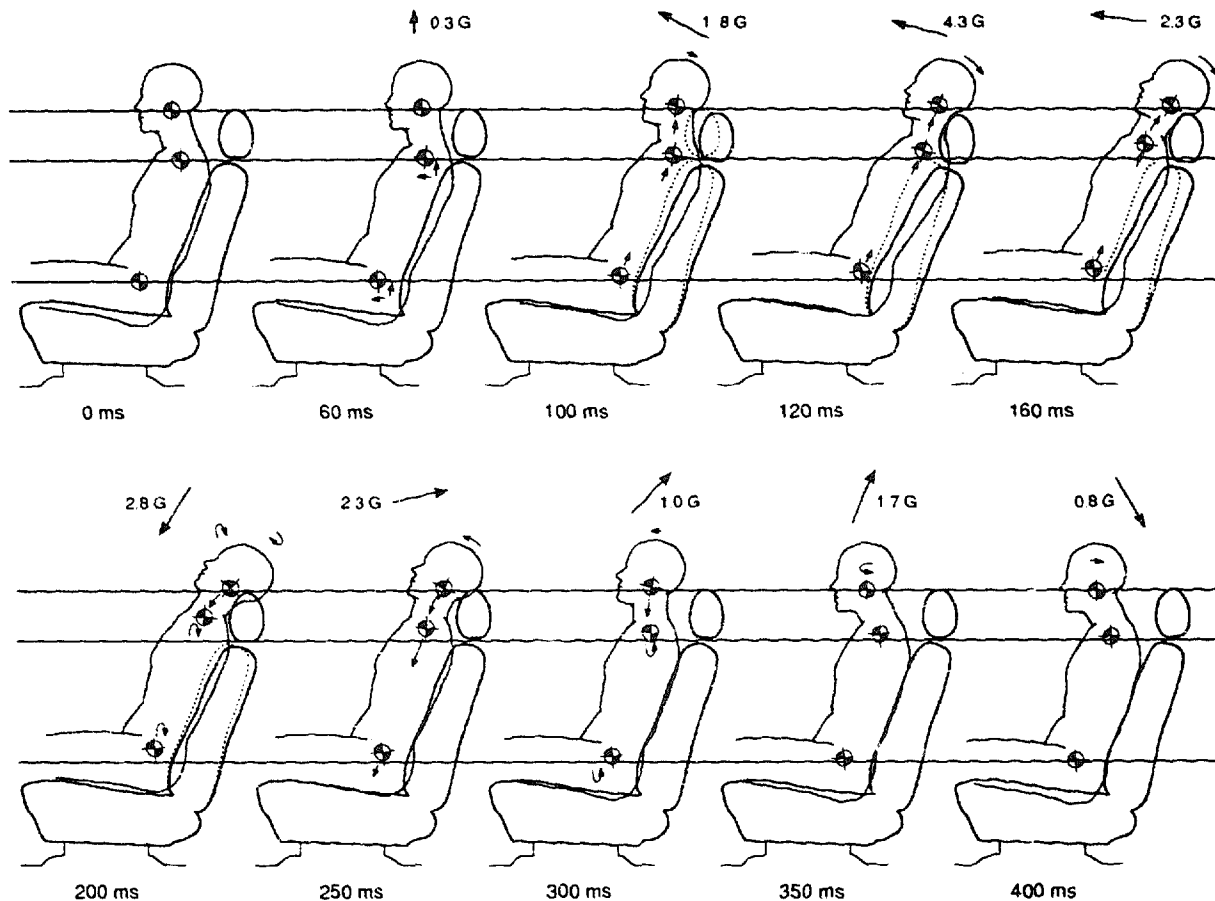


Figure 2. Head, Neck and Trunk Responses to Low Velocity Rear End Impact

subject's head and neck were still almost stationary with respect to the earth until about 120 milliseconds when, as the subject's hips and trunk rose upward on a path parallel to the rearward flexed seatback, his neck appeared to be axially compressed and straightened as the top of the cervical spine began moving upward and rearward with respect to the forward moving vehicle. Subsequently, the subject's head began a biteblock upward and rearward rotating movement with respect to the subject's shoulders. By 160 milliseconds the forward and upward movement of the subject's ascending upper torso had begun to pull the base of his neck forward into apparent tension and starting the forward motion of the subject's head, even as his occiput continued to tip downward towards the seat headrest.

Phase 3 - Head Overspeed/Torso Recovery (200 to 300 milliseconds) — At 200 milliseconds the upward motion of the subject's trunk and shoulders had ceased after about 9 centimeters (3.5 inches) of rise and the extension and

rotational angulation of his head had stopped about 45 degrees rearward from vertical. The subject's top of the cervical spine marker point had risen about 1.25 centimeters (0.5 inches) above its initial vertical position and the subject's head was starting to reverse its motion, with respect to the vehicle, into a forward arcing movement. By 250 milliseconds the forward rebounding head had not yet reached vertical, but the subject's trunk, neck and head were already descending along a path parallel to the seatback. His trunk was nearly halfway towards its starting position with respect to the seat bottom. By this time, the seatback had returned to its pre-impact normal angle and the subject's torso was rebounding forward and away from the seatback's surface. At this point the test subject's upper body was probably being actively retarded by the tightened restraint system. The restraint system had become more than normally tightened when the spring powered seatbelt retractor reeled in about 5 to 8 centimeters (2 to 3 inches) of seatbelt and shoulder harness slack that had