

ORIGINAL

Session No. 530

Effects of Velocity and Occupant Sitting Position on the Kinematics and Kinetics of the Lumbar Spine during Simulated Low-Speed Rear Impacts

**David L. Gushue, Ph.D., Bradley W. Probst, MS, Brian Benda, Ph.D., Tim Joganich, MS, CHFP, Dan McDonough, MS, Michael L. Markushewski
ARCCA Inc.
Penns Park, PA**

Background

ARCCA Inc. has investigated thousands of low-speed multi-vehicle rear-end impacts with discernibly little vehicle damage and pronounced claims of lumbar, thoracic, cervical or head injuries. Determination of a causal relationship between claimed injuries and a low-speed rear-end impact requires thorough analyses of the subject incident and knowledge of the unique tolerance level of the individual in question. Unfortunately, this task is often incorrectly given to a treating physician who may be ill-equipped to properly analyze the subject incident. Evaluations of incident severity, including the principal direction of force and delta-V, as well as the associated vehicle and occupant kinematics and kinetics are required to properly assess both the magnitude and direction of force that an occupant sustains in a low-speed rear-end impact. Therefore, a biomedical engineer who is trained in the application of the concepts and methods of mechanical engineering and the physical sciences to medicine and the human body is needed to correlate mechanisms of the claimed injuries with the mode and intensity of the energy transfer associated with the subject incident.

Historically, low-speed rear impacts have been associated with claims of whiplash injuries and it has recently been estimated that in the United States over 805,000 whiplash injuries are claimed annually, costing an estimated \$5.2 billion.¹ Throughout ARCCA's experience and research it has been observed that claimed cervical spine injuries are often associated with concurrent claims of lumbar spine injuries, such as lumbar sprains/strains, disc herniations, spondylolysis and spondylolisthesis. For example, it has been estimated that clinical and epidemiological literature demonstrates the existence of low back complaints in approximately 45 percent of cases that include claims of whiplash. Reports of the contemporaneous complaints of low back pain appear in the literature as far back as the mid-1950s and continue through the present, with most authors

¹ National Highway Traffic Safety Administration. (2001) Federal Register, Vol. 66, No. 3, pp. 967-999

reporting an incidence of low back pain of 35 to over 50 percent in cases of claimed whiplash injury.^{2,3,4,5,6,7,8}

While previous research has been conducted on the response of occupants to low-speed rear impacts, there have been no published data regarding kinetics of the lumbar spine during these incidents. For example, several studies have subjected human volunteers of various ages to multiple low-speed rear-end impacts to evaluate the injury thresholds for cervical strains and other associated injuries.^{9,10,11} These studies have provided valuable insight into the tolerance levels of the human cervical spine during low-speed rear impacts and have enabled researchers and clinicians to better understand the often improbable existence of a causal relationship between an individual's claimed cervical injuries and a specific subject incident. In addition, despite the inclusion of volunteers with various degrees of lumbar spinal degeneration, previous studies have reported a lack of relative motion in the lumbar spine and therefore a decreased likelihood of significant low back injuries in low-speed rear impacts.^{12,13}

Historically, low-speed rear impact testing with both human volunteers and anthropomorphic test devices (ATDs) has been conducted with the subject placed in what is often referred to as a Normal Seated Position. This position has often been described as that in which the subject's buttocks are squarely on the seat, their scapulas or shoulder blades are placed firmly against the seatback, and the head and chest are laterally centered on the head restraint and seatback, respectively.¹⁴ However, the possibility of an out-of-position occupant who may be leaning forward, such as to adjust a control knob for the radio, represents a situation in which relative motion and increased loading of the lumbar spine may occur. Taking this into consideration, further research and experimental data are required to provide a better understanding of the kinematics and kinetics of the lumbar spine during low-speed rear impacts.

-
- ² MM, Rosner S. Symptomatology and treatment of injuries of the neck. *NY State J Med* 55:237-242, 1955.
 - ³ AC. Soft tissue injury: long and short-term effect. In: Foreman SM, Croft AC (eds): *Whiplash Injuries: The Cervical Acceleration/Deceleration Syndrome*. Baltimore, Williams & Wilkins Co., 1988, p 293.
 - ⁴ M. Soft tissue injuries of the neck in automobile accidents: factors influencing prognosis. *J Bone Joint Surg* 56A(8):1675-1682, 1974.
 - ⁵ G, Westman G. Chronic posttraumatic syndrome after whiplash injury: a pilot study of 22 patients. *Scan J Prim Health Care* 9:135-141, 1991.
 - ⁶ T. Extracervical symptoms after whiplash trauma. *Cephalalgia* 14(3):223-227, 1994.
 - ⁷ MF, Bannister GC. The rate of recovery following whiplash injury. *Eur Spine J* 3:162-164, 1994.
 - ⁸ B, Gargan MF, Bannister GC. Soft-tissue injuries of the cervical spine: 15-year follow-up. *J Bone Joint Surg* 78-B(6):955-957, 1996.
 - ⁹ McConnell WE, Howard RP, Guzman HM, Bomar JB, Raddin JH, Benedict JV, Smith HL, and Hatsell CP. (1993). Human Test subject Kinematic Responses to Low Velocity Rear End Impacts (SAE 930889). Warrendale, PA: Society of Automotive Engineers.
 - ¹⁰ West, D. H., J. P. Gough, et al. (1993). "Low Speed Rear-End Collision Testing Using Human Subjects." *Accident Reconstruction Journal*.
 - ¹¹ Szabo, T. J., J. B. Welcher, et al. (1994). Human Occupant Kinematic Response to Low Speed Rear-End Impacts (SAE 940532). Warrendale, PA, Society of Automotive Engineers.
 - ¹² West, D. H., J. P. Gough, et al. (1993). "Low Speed Rear-End Collision Testing Using Human Subjects." *Accident Reconstruction Journal*.
 - ¹³ Szabo, T. J., J. B. Welcher, et al. (1994). Human Occupant Kinematic Response to Low Speed Rear-End Impacts (SAE 940532). Warrendale, PA, Society of Automotive Engineers.
 - ¹⁴ Benson, B.R., Smith, G.C., et al. (1996). Effect of Seat Stiffness in Out-of-Position Occupant Response in Rear-End Collisions (SAE 962434). Warrendale, PA, Society of Automotive Engineers.

Therefore, the purpose of this study was to examine and quantify the effects of sitting position on the kinematic and kinetic responses of an anthropomorphic test device in simulated low-speed rear impacts, with a specific focus on the kinetics of the lumbar spine and their relative values as compared to injury assessment reference values.

Methodology

A series of sled tests were conducted by ARCCA Inc. to investigate the effects of sitting position on the kinematic and kinetic responses of an anthropomorphic test device subjected to simulated low-speed rear-end collisions. A seated ATD was located on a sled which was accelerated backwards prior to being decelerated by an energy-absorbing material mounted on a striker plate. Impact between the rolling sled and the energy-absorbing material created an acceleration time history that simulated a low-speed rear impact. The primary components of the test setup were a flatbed test fixture, a production automobile driver's seat, and the ATD itself. Sensors and data acquisition hardware completed the setup.

Test Hardware

The test fixture was a 16 foot long, trailer-mounted, flat test track on which ran a guided sled. The sled was essentially a flat steel platform (4 feet long, 2 feet wide) attached to three axles which were supported by polyurethane wheels. To ensure one-dimensional motion of the sled, the wheels ran through a pair of guides fixed to the test track. Mounted at the end of the track was an energy-absorbing material that arrested the sled's movement. To achieve the desired impact speeds, a cable-pulley-weight system was attached to the sled. When used, the dropping weights increased the kinetic energy and therefore the speed of the sled. Energy-absorbing frangible material was attached in series with the striker plate to provide the desired the amplitude and duration of the acceleration pulse applied to the sled.

A production driver's seat taken from a 1999 Buick Park Avenue was mounted to the sled platform. This was a single occupant (bucket type) seat with a manual three-point seat belt system, fixed latch plate, and end-push buckle. All belt anchor points were mounted to the seat itself. Previous testing with an exemplar seat demonstrated that this seat configuration has a seatback strength in excess of 30,000 inch-pounds measured about the hinge point, thereby eliminating potential seatback failure during repetitive testing. For our sled testing, fore-aft position of the seat was positioned at the midpoint of the total travel and the head restraint was located in the full-down position.

The ATD utilized for this testing was a 50th percentile male Hybrid III dummy with a pedestrian pelvis. The ATD had a nominal height of 175 cm (69 inches) and weight of 79 kg (173 pounds). An overall view of the test setup, including the test fixture, seat, and the ATD is shown in Figure 1.

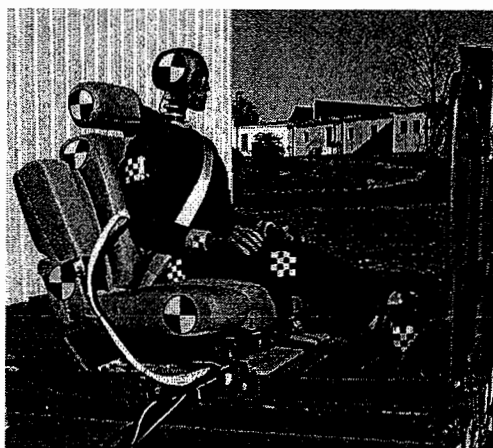


Figure 1. Overall view of test setup

Instrumentation and Data Acquisition

Multiple sensors were utilized to quantify the simulated impact environment and the response of the ATD during testing. An optical time trap (NAIS UZB2222/UZB2120 (pair)) mounted at the end of the track determined the speed of the sled immediately prior to its impact with the striker plate. A uniaxial accelerometer (EGAX-F-25 Accelerometer) attached to the flat plate of the sled recorded the longitudinal acceleration time history (A_x). Three standard digital video cameras were used to document the kinematics of the ATD during the testing.

The Hybrid III test dummy instrumentation included a triaxial linear accelerometer (EGV3-F-250 Accelerometer) mounted in the head, a six-component load transducer in the upper cervical spine (Denton Load Cell Model 1716A), and a six-component load transducer in the lumbar spine (Denton Load Cell Model 1914A). These load transducers measured the three components of force (anterior-posterior shear (F_x), lateral shear (F_y), and tension -compression (F_z)) and the three components of moments (lateral bending (M_x), flexion-extension in the sagittal plane (M_y), and torsion (M_z)). Data from the optical time trap, the sled-mounted accelerometer, and the ATD sensors were sampled at a rate of approximately 10,000 Hertz (Hz). Channel frequency class 1000 hardware filters were used with all data channels¹⁵.

Testing Design/Matrix

The testing design evaluated dummy response data (independent variable) against two dependent variables, impact speed and initial sitting posture. A test matrix consisting of two impact speeds and three pre-impact dummy sitting postures gave a total of six combinations of dependent test parameters. Two tests were run for each combination of test parameters for a total of 12 tests.

For this study, tests were conducted at target impact speeds of 8 kilometers-per-hour (kph) (5 mph) and 12 kph (8 mph). The three sitting postures investigated were: 1) nominal or in-position (centered in seat with three inches between the posterior head of the ATD and the seatback head restraint), 2) slightly out-of-position (centered in seat but leaning forward with six inches between the posterior head of the ATD and the seatback head restraint), and 3) out-of-position (centered in

¹⁵ Society of Automotive Engineers, Inc. (1995) Instrumentation for Impact Test – Part 1 – Electronic Instrumentation, SAE J211-1.

seat but leaning forward with 20 inches between the posterior head of the ATD and the seatback head restraint). These three sitting postures are shown in Figure 2. Note, a light weight string tether around the neck was utilized to maintain the forward-leaning position of the ATD for all of the out-of-position tests however, this tether separated with minimal force and did not alter the motion of the occupant.

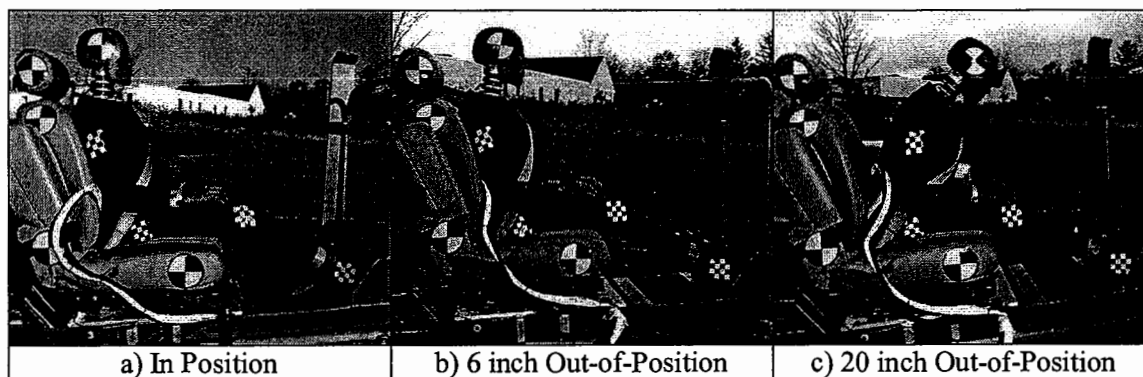


Figure 2. Three sitting postures tested

Results

A total of twelve sled tests were performed, six at a target velocity of 8 km-per-hour and six at a target velocity 12 km-per-hour. Representative plots of sled acceleration during both the 8- and 12 kph impacts are shown in Figure 3.

Averaged sled and pulse characteristics for all of the sled tests are shown in Table 1. As shown, the test method utilized for this study yielded consistent and repeatable acceleration pulses at the targeted velocities. During this testing, an increase in sled velocity from 8- to 12 kph was associated with a concurrent increase in sled acceleration of 65% and a decrease in the pulse duration of 20% (Table 1).

Analyses of the test video permitted a determination of the kinematic response of the ATD during the simulated low-speed rear impact tests. Given the nature of the test setup and the controlled motion of the sled, only sagittal plane motion was considered during these analyses. During all tests, rearward motion of the head resulted in contact with the head restraint, however all rearward motion of the head and torso of the subject ATD was arrested and well controlled by the head restraint and seatback, respectively. During the in-position and 6 inch out-of-position tests, no motion of the ATD's lumbar spine, pelvis, knees or feet were observed. Motion of the lumbar spine during the 20 inch out-of-position tests occurred as the ATD moved rearward prior to coming into contact with the seatback, however this motion was well controlled by the seatback structure. As shown in Figure 4, slight ramping of the ATD was observed relative to the seatback during the out-of-position tests, however during all tests the head restraint prevented the hyperextension of the head and neck from occurring. In addition, no significant forward rebound of the belted ATD away from the seatback structure was observed during these tests.

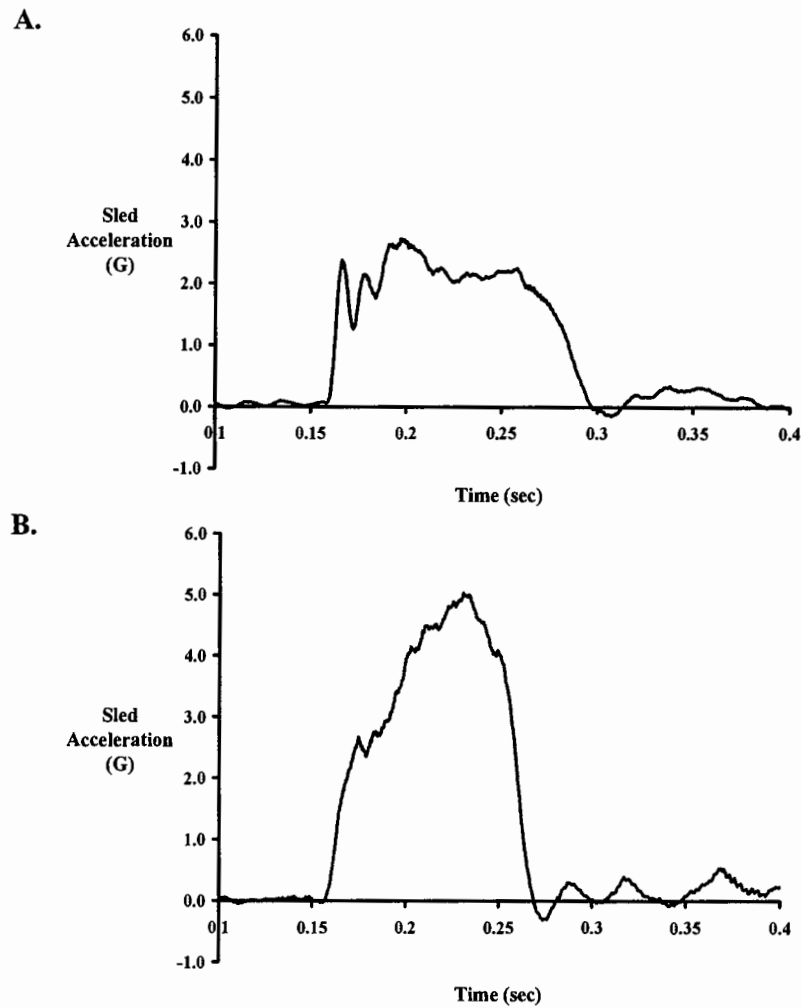


Figure 3. Representative sled acceleration pulses for 8 km-per-hour (A) and 12 km-per-hour (B) tests.

Table 1. Recorded Test Parameters.

	8 Km-Per-Hour	12 Km-Per-Hour
	Mean (S.D.)	Mean (S.D.)
Sled Velocity (kph)	8.4 (0.2)	12.2 (0.3)
Sled Acceleration (G)	3.1 (0.2)	5.1 (0.3)
Pulse Duration (msec)	154 (10)	123 (13)

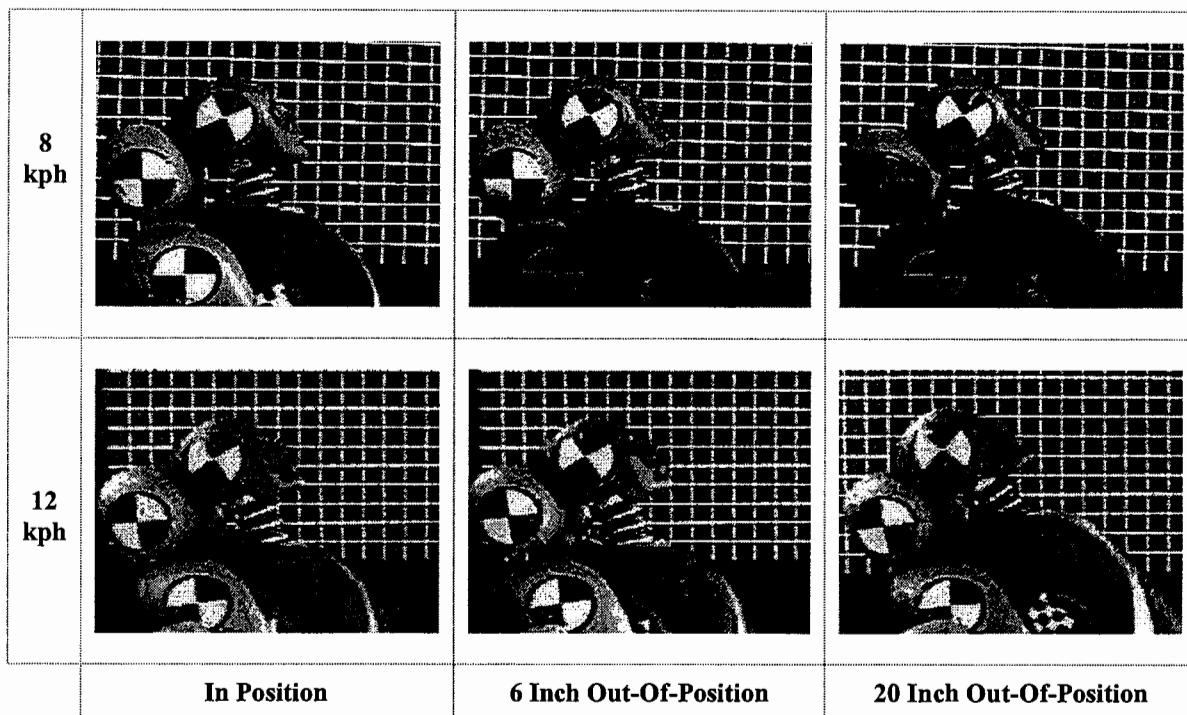


Figure 4. Still frames demonstrating the point of peak vertical ramping of the ATD.

Summaries of the peak data values for the lumbar spine during both the 8- and 12 kph tests are shown in Tables 2 and 3, respectively. During the 8 kph tests, the lumbar spine posterior shear, compression and tension forces increased as the torso of the ATD became further out-of-position (Table 2). Limited injury criteria data are available for the lumbar spine, with the most widely accepted injury assessment reference value being 1500 lbs for the peak lumbar spine compression force.¹⁶ As shown in Table 2, the peak lumbar compression force measured during these tests was 43.1 lbs (20 inch out-of-position), which represented a minimum factor of safety of 35 as compared to the associated injury assessment reference value. As expected, during the 8 kph tests, the lumbar spine extension moment increased as the torso of the ATD became further out-of-position.

Similar to the data measured during the 8 kph tests, during the 12 kph tests the lumbar spine posterior shear, compression and tension forces increased as the torso of the ATD became further out-of-position (Table 3). As shown in Table 3, the peak lumbar compression force measured during these tests was 120.8 lbs (20 inch out-of-position), which represented a minimum factor of safety of 12 as compared to the associated injury assessment reference value of 1500 lbs. In addition, similar to the 8 kph tests, the lumbar spine extension moment increased as the torso of the ATD became further out-of-position for the 12 kph tests.

¹⁶ Federal Aviation Administration Safety Standard: Emergency Landing Conditions, 25.561.

Table 2. Peak Lumbar Forces and Moments for 8 Km-Per-Hour Tests.

	In Position		6 Inch Out-of-Position		20 Inch Out-of-Position	
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Lumbar Anterior Shear Force (lbs)	23.4	25.3	21.3	25.0	7.1	5.7
Lumbar Posterior Shear Force (lbs)	18.3	15.2	30.9	26.6	78.3	76.9
Lumbar Compression Force (lbs)	8.3	9.2	13.7	13.7	43.1	35.1
Lumbar Tension Force (lbs)	14.2	18.8	32.7	37.7	64.2	72.3
Lumbar Flexion Moment (in-lbs)	149.9	220.6	193.5	268.4	33.7	34.7
Lumbar Extension Moment (in-lbs)	76.5	101.3	136.9	140.0	747.0	803.1

Table 3. Peak Lumbar Forces and Moments for 12 Km-Per-Hour Tests.

	In Position		6 Inch Out-of-Position		20 Inch Out-of-Position	
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Lumbar Anterior Shear Force (lbs)	82.1	74.9	15.4	75.0	18.6	33.5
Lumbar Posterior Shear Force (lbs)	18.8	27.1	6.9	28.0	179.8	162.1
Lumbar Compression Force (lbs)	23.7	21.82	6.6	27.32	120.8	100.3
Lumbar Tension Force (lbs)	29.8	52.6	13.6	50.8	139.2	142.6
Lumbar Flexion Moment (in-lbs)	378.9	376.8	42.4	254.4	2.1	83.1
Lumbar Extension Moment (in-lbs)	71.9	65.3	47.1	135.7	1364.5	1270.8

Summaries of the peak data values for the head and neck of the ATD during both the 8- and 12 kph tests are shown in Tables 4 and 5, respectively. During the 8 kph tests, the peak resultant head accelerations ranged from 5.9 to 8.9g, with an increasing trend as the ATD became further out-of-position (Table 4). However, these data were well below the associated injury assessment reference

value for peak head acceleration of 400g.¹⁷ Likewise, the peak neck tension forces ranged from 90.7 to 223.5 lbs, with an increasing trend as the ATD became further out-of-position, which were well below the associated injury assessment reference value of 937 lbs.¹⁸ In addition, the data values recorded for the peak neck flexion and extension moments for the ATD during the 8 kph tests were well below the associated injury assessment reference values (Table 4).¹⁹ In accordance with these individual neck variables, the maximum Nij values ranged from 0.07 to 0.16 for the 8 kph tests, which were well below the associated injury assessment reference value of 1.0.²⁰

During the 12 kph tests, the peak resultant head accelerations were well below the associated injury assessment reference value for peak head acceleration of 400g (Table 5).²¹ In addition, similar to the 8 kph tests, the peak neck tension forces, flexion moments, and extension moments were well below the associated injury assessment reference values.²² In accordance with these individual neck variables, the maximum Nij values ranged from 0.05 to 0.45 for the 12 kph tests, which were well below the associated injury assessment reference value of 1.0 (Table 5).²³

Table 4. Peak Head and Neck Data Values for 8 Km-Per-Hour Tests.

	In Position		6 Inch Out-of-Position		20 Inch Out-of-Position	
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Resultant Head Acceleration (G)	5.9	5.9	7.7	8.1	8.9	7.2
Neck Tension Force (lbs)	90.7	118.8	145.2	158.9	223.5	203.0
Neck Flexion Moment (in-lbs)	31.8	27.2	17.2	17.4	41.8	54.1
Neck Extension Moment (in-lbs)	111.8	119.6	153.7	151.2	148.9	133.2
Nij	0.07	0.09	0.10	0.10	0.16	0.15

¹⁷ Federal Motor Vehicle Safety Standard 218: Motorcycle Helmets, 49 CFR 571.218.

¹⁸ Federal Motor Vehicle Safety Standard 208: Occupant Crash Protection, 49 CFR 571.208.

¹⁹ Federal Motor Vehicle Safety Standard 208: Occupant Crash Protection, 49 CFR 571.208.

²⁰ Federal Motor Vehicle Safety Standard 208: Occupant Crash Protection, 49 CFR 571.208.

²¹ Federal Motor Vehicle Safety Standard 218: Motorcycle Helmets, 49 CFR 571.218.

²² Federal Motor Vehicle Safety Standard 208: Occupant Crash Protection, 49 CFR 571.208.

²³ Federal Motor Vehicle Safety Standard 208: Occupant Crash Protection, 49 CFR 571.208.

Table 5. Peak Head and Neck Data Values for 12 Km-Per-Hour Tests.

	In Position		6 Inch Out-of-Position		20 Inch Out-of-Position	
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Resultant Head Acceleration (G)	12.8	14.2	13.8	34.3	16.5	17.4
Neck Tension Force (lbs)	134.6	137.8	37.8	144.3	321.9	350.1
Neck Flexion Moment (in-lbs)	103.1	98.6	20.3	92.0	208.3	199.1
Neck Extension Moment (in-lbs)	131.9	116.6	39.9	146.6	257.4	264.6
Nij	0.16	0.15	0.05	0.18	0.42	0.45

Discussion

This study represents the first investigation known to the authors into the effects of sitting position on the kinematic and kinetic responses of an anthropomorphic test device in simulated low-speed rear impacts, with a specific focus on the kinetics of the lumbar spine. Twelve sled tests were successfully conducted with an instrumented 50th percentile ATD seated in a production driver's seat at both 8- and 12 kph with acceleration pulses indicative of typical low-speed vehicle-to-vehicle impacts. Overall, the peak values of the kinetic variables that were measured were all well below the accepted injury assessment reference values for both the in-position and out-of-position tests.

In general, examination of our data for the head and neck of the instrumented ATD reveals that the magnitude of these variables are consistent with those previously reported for both in-position and out-of-position occupants during low-speed rear impacts.²⁴ Therefore, our test setup and methodology were found to produce accurate and repeatable data, which further validates our ability to investigate the kinetics of the lumbar spine during simulated low-speed rear impacts.

Tissue stress and strain develop when forces act on the human body. During a rear-end collision, an in-position occupant whose spine is aligned with the seatback structure receives a force that is distributed across the vertebral segments. Due to this distributed loading there is little differential force along the structure of the spine, thereby diminishing the expectation for the development of significant shear or bending stresses and strains. However, the effects of an out-of-position occupant whose spine may not be in contact with the seatback at the moment of impact were previously unknown. Our study has demonstrated that for both in-position and out-of-position occupants the peak lumbar spine compression forces were well below the established injury

²⁴ Benson, B.R., Smith, G.C., et al. (1996). Effect of Seat Stiffness in Out-of-Position Occupant Response in Rear-End Collisions (SAE 962434). Warrendale, PA, Society of Automotive Engineers.

assessment reference value, thereby indicating the risks for associated injuries of the lumbar spine would be very low for all tests. Although limited data are available for injury assessment reference values of the lumbar spine, previous experimental studies have demonstrated that cadaveric lumbar intervertebral discs can sustain up to 651 lbs of shear force without incurring an injury.²⁵ During this study, the data for peak anterior or posterior lumbar shear forces ranged from 5.7 to 179.8 lbs. Therefore, despite being as far as 20 inches out-of-position in a forward flexed orientation, our data demonstrate that lumbar spine kinetics fail to exceed previously defined levels of injury during low-speed rear impacts.

In summary, our study provides valuable data on the kinetics of the lumbar spine in simulated low-speed rear impacts for both in-position and out-of-position occupants, thereby imparting further insight into a causal relationship between an individual's claimed lumbar injuries and a specific subject incident. These data emphasize the inability of a low-speed rear impact to induce significant loads on the lumbar spine of a properly supported occupant. Therefore, our study supports the understanding that low-speed rear impacts fail to impart sufficient energy to the lumbar spine so as to induce a significant injury, such as lumbar vertebral body fractures or disc herniations.

²⁵ Begeman, P.C., Visarius, H. (1994). Viscoelastic Shear Responses of the Cadaver and Hybrid III Lumbar Spine (SAE 942205). Warrendale, PA, Society of Automotive Engineers.