ORIGINAL ARTICLE

Significant Spinal Injury Resulting From Low-Level Accelerations: A Case Series of Roller Coaster Injuries

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ABSTRACT. Freeman MD, Croft AC, Nicodemus CN, Centeno CJ, Elkins WL. Significant spinal injury resulting from low-level accelerations: a case series of roller coaster injuries. Arch Phys Med Rehabil 2005;86:2126-30.

Objectives: To describe a cohort of significantly injured roller coaster riders and the likely levels of acceleration at which the injuries occurred, and to compare these data with contemporary efforts to define a lower limit of acceleration below which no significant spinal injury is likely to occur.

Design: A retrospective case series of roller coaster ride–induced significant spinal injuries.

Setting: Injury incident records and emergency medical service records for the Rattler roller coaster in San Antonio, TX, were evaluated for a 19-month period in 1992 and 1993. Medical records for the more significant injuries were also reviewed and the specific injuries were tabulated, along with the demographics of the cohort.

Participants: There were 932,000 riders of the Rattler roller coaster, estimated to represent between 300,000 and 600,000 individual riders.

Interventions: Not applicable.

Main Outcome Measures: Injury incident reports and medical record review.

Results: It is estimated that there were a total of 656 neck and back injuries during the study period, and 39 were considered significant by the study inclusion criteria. Seventy-two percent (28/39) of the injured subjects sustained a cervical disk injury; 71% of these injuries were at C5-6 (15 disk herniations, 5 symptomatic disk bulges) and 54% were at C6-7 (11 disk herniations, 4 symptomatic disk bulges). In the lumbar spine, the most frequent injury was a symptomatic disk bulge (20% of the cohort), followed by vertebral body compression fracture (18%), and L4-5 or L5-S1 disk herniation (13%). Accelerometry testing of passengers and train cars indicated a peak of 4.5 to 5g of vertical or axial acceleration and 1.5g of lateral acceleration over approximately 100ms (0.1s) on both.

Conclusions: The results of this study suggest that there is no established minimum threshold of significant spine injury. The greatest explanation for injury from traumatic loading of the spine is individual susceptibility to injury, an unpredictable variable.

Key Words: Disk, herniated; Rehabilitation; Spine; Whiplash injuries.

THE LEVEL OF FORCE at which significant spinal injury can occur is a topic that has generated much discussion in the literature over the past 30 years. Various researchers have attempted to experimentally quantify a minimum threshold for spinal injury in motor vehicle collisions by examining the human response to low-speed crash testing using both live volunteers, cadavers, and anthropometric dummies.[1-3] Others have attempted to gauge risk of injury to traumatically induced spine loads by examining the muscular strength of the neck with static loads.[4] In general, the results of such experimental studies cannot be extrapolated to an injury threshold for real-world crashes, because such crashes do not involve cadavers or human volunteers resisting a static load.

Tencer and Mirza[5] have postulated a minimum rear-impact collision cervical spine injury threshold of 45 foot-pounds of torque at the occipital condyles, based on averaged values extrapolated from the volunteer crash test and cadaver testing literature. This article suffers from numerous methodologic flaws that tend to invalidate the conclusions of the authors regarding a minimum threshold of injury for the cervical spine. Even a theoretical minimum injury threshold cannot be based on population averages because an average gives no indication of the lower limit of the data range from which it was derived. Additionally, the degree of error inherent in the derivation of an average from dissimilar studies with small study numbers (typically, 1 to 5) is vast, and precludes any meaningful interpretation of such a calculation.

Another group of investigators devised a study in which the peak acceleration measured at the head during activities of daily living was compared with the peak head acceleration measured during volunteer crash testing.[6] Because several of the acceleration values measured during the activities were comparable to those of the crash testing, the authors concluded that there was a similar risk of injury between real-world low-speed crashes and plopping in a chair or sneezing. The logical errors in such a study are readily apparent: the fact that 1 parameter (peak head acceleration) of 2 entirely different events is comparable does not necessarily imply comparability of other parameters (injuriousness). Resultant peak head acceleration has not been shown to be a valid construct for the injuriousness of an event; some people will sustain neck injury at lower levels of peak head acceleration than others.[7]

Because of the wide variability in real-world crashes in vehicles, crash conditions, and factors relating to occupant injury susceptibility, the results of experimental studies are typically not generalizable to the at-risk population. Although they may give a crude estimate of average injury thresholds in the experimental population, they cannot be used to establish a minimum injury threshold for real-world crashes.[8] This is due, in part, to the fact that ethical constraints dictate that volunteer crash testing be accomplished with healthy and informed sub-

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jects, and in a manner least likely to result in injury. Real-world crash victims are not necessarily healthy, never informed, and the crashes occur in a random fashion. A human volunteer crash test from which no injury results provides evidence that it is *possible* to undergo such testing without sustaining injury, but gives no indication as to whether injury can or cannot occur with repeated testing, much less in real-world crashes at similar force levels.

Significant spine injuries (ie, disk herniation) are a relatively rare occurrence with minimal-damage crashes, and thus must be evaluated with study designs suitable for infrequent outcomes. In a study of rear-impact crash injuries in 37 states, Farmer et al[9] found that only 1 in 5 men and 1 in 4 women sustain any cervical spine injury after crashes with $500 or less in property damage. The incidence of more significant injury such as disk herniation would be considerably less, although it was not described by these authors. To study rare outcomes, either very large groups of exposed subjects must be evaluated or subjects need to be selected on the basis of their injuries (case-control design). Small experimental studies of injury exposure such as human volunteer crash tests are unlikely to produce the relatively rare significant spinal injuries that are the outcome of interest.

For these reasons, research pertaining to human injury thresholds can only be accomplished with observational study; that is, analysis of real-world injury exposures and their outcomes. Such study is difficult with motor vehicle collision–induced injury patterns because it is not always feasible to accurately determine the amount of force that occurred in a crash after the fact, something that is essential if a valid injury threshold is to be derived.

Accident reconstruction is frequently employed in cases in which injury presence or severity is disputed, in order to estimate the change of velocity of a struck vehicle in a low-speed crash. The change in velocity is often used to estimate the head acceleration value (g force) in order to gauge the peak level of force experienced by the occupant. Siegmund et al[10] showed the large error inherent in converting velocity change into peak head acceleration when they measured the peak head acceleration in a group of 39 male and female volunteers exposed to a rear-impact collision with an 8-km (5-mph) change in velocity. These authors reported head peak acceleration ranging from 6.7 to $12g$ among their test cohort, all of whom were seated in the same vehicle in near identical position. It is clear, then, that there is significant inherent error in attempting to predict peak head acceleration by relying solely on vehicle velocity change.

One experimental design that could help define an injury threshold would be a population-based study in which hundreds or thousands of randomly selected subjects are exposed to identical low-level accelerations and then evaluated for signs of injury. For obvious reasons, however, such a design is impractical from a logistic and ethical perspective.

There is a naturally occurring setting in which large numbers of relatively unselected subjects are exposed to similar levels of acceleration, and that is amusement park rides; roller coasters in particular. Roller coasters deliver a near identical level of acceleration to hundreds of thousands of subjects over a period of years, and are, in effect, a naturally occurring experimental laboratory of human response to relatively low-level accelerations. Typically, roller coaster rides deliver peak car accelerations of 2 to $3g$, but in attempting to make the rides more exciting, some roller coaster manufacturers have increased the level of peak acceleration to more than $6.5g$.[11]

Injuries can and do occur on roller coasters; the Consumer Product Safety Commission estimates that there were 10,700 emergency department visits in 2000 resulting from amusement park ride injuries.[12] Most injuries occurred on fixed amusement park rides, like roller coasters, as opposed to the portable type. There are numerous case studies and case series documenting roller coaster ride–induced injuries to the brain, including subdural hematoma,[13,14] vertebrobasilar artery dissection and carotid artery occlusion,[15] as well as subarachnoid hemorrhage.[16] However, a MEDLINE literature review of 1966 through 2004 using the terms *roller coaster* and *amusement parks* revealed no documented roller coaster ride–induced injuries of the spine.

In the current study, we comprehensively reviewed incident (injury) reports during a 19-month period of operation of a single roller coaster ride in San Antonio, TX. The goal of this review was to identify cases of spinal injury beyond the level of sprain or strain injury to determine if such injuries can and do occur in association with the accelerations experienced during roller coaster rides.

METHODS

Injury incident records kept by the operators of the Rattler roller coaster for the period March 28, 1992, through October 22, 1993 (≈19mo), were examined for significant (beyond a sprain or strain diagnosis) spinal injuries that occurred on the ride. For the more serious injuries, emergency medical response and medical treatment records were obtained, and information on the nature and severity of injuries, as well as treatment, were tabulated.

The inclusion criteria for the significant spinal injury cohort were as follows: (1) an incident report and/or emergency medical response report reflecting immediate onset of symptoms following the roller coaster ride; (2) medical records were obtainable that described a diagnostic severity level more serious than sprain or strain (eg, disk or bony injury); and (3) diagnostic imaging was used to validate the diagnosis (ie, magnetic resonance imaging, computed tomography, plain radiography).

Additionally, the date of injury, age, sex, and height and weight of the injured subjects were tabulated. Information regarding the peak occupant acceleration levels occurring on the Rattler roller coaster as established by accelerometry testing conducted by an independent engineering consultant was also evaluated and compared with acceleration levels described in the literature on human volunteer crash testing.

RESULTS

During the 19 months of the study, there were approximately 932,000 riders of the Rattler roller coaster. Based on a 4-month sample (the longest period of intact record keeping) of total injury occurrence during the study period (regardless of severity) in which there were 138 spinal injuries reported, it is estimated that there were approximately 600 to 700 neck and back injuries between March 28, 1992, through October 22, 1993, yielding a spinal injury rate of 1 per 1330 to 1550 rides. Of these reported injuries, 39 were found that fit the study inclusion criteria. The medical records for the 39 subjects were obtained as a result of litigation arising from persisting claims of injury. Subjects among the 600 to 700 total injured who may have been significantly injured but who did not make a legal claim of injury were not captured in the study cohort.

The point on the roller coaster ride at which the injury was reported to have occurred most frequently, by either the injured occupant or another passenger, was the bottom of the first drop, a section of the ride following a 49.8-m (166-ft) drop, in which the train reaches an estimated 112-km (70-mph), and then rolls

Table 1: All Spine Injuries

Injuries	Neck n (%)	Low Back n (%)	Total n (%)	χ^2 Test*
Total injuries for 19-mo study period, estimated from 4-mo sample	371	285	656	
Location of injuries				
First drop	238 (64)	175 (61)	413 (63)	0.52
Other curve or drop	62 (17)	43 (15)	105 (16)	0.32
Unknown	71 (19)	67 (24)	138 (21)	1.85
Total	371 (100)	285 (100)	656 (100)	

*3.84=χ^2 crit.

Table 3: Total Cervical Spine Injuries Among 39 Study Subjects

Injury Type	No. of Subjects With Injury (% of Total Subjects*)
C5-6 HNP	15 (38)
C6-7 HNP	11 (28)
C5-6 symptomatic disk bulge	5 (13)
C6-7 symptomatic disk bulge	4 (10)
C4-5 HNP	4 (10)
Other symptomatic disk bulges	2 (5)
C1-2 instability and cord contusion	1 (3)
C5 compression fracture	1 (3)

*The total percentage of injuries totals more than 100% because some subjects had more than 1 injury.

to the right and into a climb to the next curve. The location on the ride at which the injuries occurred was analyzed by neck or back injury, and then for all spinal injuries combined (table 1). No significant differences were found between neck and back injuries by place of injury, using chi-square analysis with 1 degree of freedom. Sixty-three percent of all spine injuries occurred in the first drop, with 21% of the remaining injuries occurring in unknown sections of the roller coaster, and the final 16% of injuries occurring in sections other than the first drop. Of the 39 significant injury cases, all but 1 were identified as having occurred at the first drop.

As indicated in table 2, the 39 subjects in the significant injury cohort were 23% male and 77% female, with a mean age ± standard deviation of 37.4±9.1 years. The estimated mean body mass index for the men was 26.6±4.8kg/m^2 and for the women was 22.0±3.5kg/m^2.

Based on a medical record review, 72% (28/39) of the cohort sustained a cervical disk injury, and 71% of these injuries were at C5-6 (15 herniated disk [herniated nucleus pulposus; HNP], 5 symptomatic disk bulges attributed to the roller coaster injury by a medical provider), while 54% were at C6-7 (11 HNP, 4 symptomatic disk bulges attributed to the roller coaster event by a medical provider) (table 3). There was 1 case of a vertebral body compression fracture at C5, and another of a spinal cord contusion secondary to a displaced os odontoideum in a 12-year-old girl.

In the lumbar spine, the most frequent injury was a symptomatic disk bulge (20% of the cohort), followed by vertebral body compression fracture (18%), and L4-5 or L5-S1 HNP (13%) (table 4).

Treatment for the injuries was surgery in 56% (22/39) cases, with the majority requiring anterior cervical diskectomy and fusion at either C5-6 (28%) and/or C6-7 level (28%) (table 5). A total of 11% of the cohort (4 subjects) underwent a surgical procedure of the lumbar spine, and the 12-year-old girl with the displaced os odontoideum underwent a C2-3 fixation.

In 1994, accelerometry testing of passengers and train cars passing through the first drop was performed on several occasions by independent engineering firms at the request of various parties associated with the injury litigation. Three different reports of accelerometer testing were reviewed (from experts on both sides of the litigation) and there was general agreement that the first drop produced 4.5 to 5.0*g* of vertical or axial acceleration and 1.5*g* of lateral acceleration over approximately 100ms (0.1s) on both the occupants (in peak head acceleration) and the train cars. In 1994 the Rattler roller coaster was modified to reduce peak accelerations.

DISCUSSION

The primary purpose of this report was to present data on spinal injuries occurring in a group of roller coaster riders. The reader is cautioned against extrapolation of the data from this study to other roller coasters because of large differences in the way various rides are constructed, and the manner in which the occupants are protected in the train cars.

An important factor that may have led to overreporting of spinal injuries in the present study is the fact that all of the cases that were included for study involved litigation. This effect was likely minimized by the inclusion criteria, in that the injury had to be immediately apparent during or shortly after the ride, as well as validated by medical diagnosis and imaging.

However, underreporting was more likely than overreporting. Injuries that became apparent some time after the ride were not included in the study, regardless of severity. Injuries that were immediately apparent and significant but not associated with litigation were not included in the study. Additionally, the definition of what was a "significant" injury was limited by what could be readily verified by medical imaging. Injuries that require specialized diagnostic techniques for identification, such as facet derangements (diagnosed with spinal facet diagnostic blocks) and painful but imaging-occult disk derange-

Table 2: Significant Injury Study Cohort

Characteristic	Men	Women	Total
Age (y)	39.2±7.4	36.9±9.5	37.4±9.1
Height (cm/in)	181.6(71.5)±8.1(3.2)	163.3(64.3)±7.1(2.8)	
Weight (kg/lb)	87.9(193.8)±20.9(46.0)	58.2(128.3)±9.2(20.3)	
BMI (kg/m^2)	26.6±4.8	22.0±3.5	
Sex, n (%)	9 (23)	30 (77)	χ^2 test=14.57*

NOTE. Values are mean ± standard deviation or as otherwise indicated.
Abbreviation: BMI, body mass index.
*3.84=χ^2crit.

ments (diagnosed with diskography) were not included in the study.

Thus, the value of the examination of the study cohort lies in describing a small injured subgroup within a large group of uninjured roller coaster riders, and in describing the likely acceleration levels at which those injuries occurred, but not in describing an injury rate that is applicable to other settings.

There are several conclusions that can be drawn regarding the cumulative risk of spinal injury in the current study, given a few assumptions about the characteristics of roller coaster riders (no normative data are available on such characteristics), keeping in mind the fact that the conclusions are limited by the strength of the assumptions. There were an estimated 656 spinal injuries among approximately 932,000 rides. The 932,000 rides undoubtedly consisted of a lesser number of total riders because many would have ridden the roller coaster more than once. If the average number of rides per rider could be assumed (based on the authors' experience with roller coasters) to range from 1.5 to 3, then the cumulative risk of spinal injury, per rider, ranged from .001 to .002, and the risk of significant spinal injury ranged from .00006 to .00013.

Another assumption is with regard to the average age of the uninjured riders versus that of the study cohort. As no normative data could be found regarding the average age of roller coaster riders, the authors again relied on experience to speculate that the average age of the uninjured riders was likely significantly lower than the average age of 37.4 years of the study cohort. Intuitively, this assumption makes sense given the fact that, in asymptomatic populations, disk annular degradation is much more prevalent in the fourth decade than in earlier decades, yet disk nuclei are still relatively well hydrated.[17] Given the rarity of injury among Rattler roller coaster riders, it is not unreasonable to conclude that the more significant injuries occurred in those riders with some asymptomatic injury diathesis; whether unknown preexisting disk derangement, for example, the os odontoideum in the case of the 12-year-old girl, or some other condition.

An indisputable finding of the present study is that gender was a significant risk factor for injury, with girls and women comprising 77% of the injured subjects. This finding is in agreement with those of other authors who have reported on the incidence of real-world crash injuries.[18]

Some researchers argue that there is a biomechanically derived injury threshold of peak head acceleration that must be surpassed before spinal injury can occur.[5] Such theoretical injury thresholds are based on averages derived from experimental studies of prepared and healthy volunteers and cadavers—2 populations that cannot serve as valid surrogates for the general population. Although experimental biomechanical data have been relied on for generalized applications, for example, the derivation of a femur load fracture threshold for which the interior of an automobile can be designed to afford greater protection in the event of a frontal impact collision, there is no credible evidence at the present time that such a threshold exists for cervical spine injuries. Even if such a threshold existed, the results of the present study illustrate the fact that it would be unlikely to include the minority of the population that is at risk of significant spine injury in low-level accelerations.

Peak head acceleration is a poor indicator for the injuriousness of an event. This fact is borne out by the research of Allen et al[6] who reported that some typically noninjurious but controlled activities such as "plopping in a chair" can generate as much peak acceleration as has been reported in experimental rear-impact collisions. While this may seem counterintuitive, it is important to note that peak head acceleration does not necessarily reflect the level of force transmitted through the spine, and thus does not necessarily correlate with the injuriousness of an activity.

In recognition of this paradox, a Neck Injury Criterion index has been developed to quantify the differential acceleration and differential velocity between the head and T1, in an attempt to better describe the level of force transmitted through the cervical spine in a rear-impact collision.[19] In a continuation of the effort to more accurately describe the cervical injury mechanism of rear-impact collisions, Grauer[20] and Kaneoka[21] and their colleagues have demonstrated potentially injurious aberrant intersegmental motion in the cervical spine that occurs before rearward rotation and peak acceleration of the head. The results of such research illustrate the burgeoning concept that peak head acceleration is related to but not necessarily directly correlated to the injuriousness of rear-impact acceleration.

The variables that likely account for the largest proportion of variation in outcome in the present study are the physical condition, individual head-neck-torso geometry, and degree of preparatory muscular bracing of the individual subjects at the time of the exposure to the peak accelerations. This assumption can be reasonably extrapolated to real-world traumatic exposures, such as rear-impact collisions, in which outcomes range from no injury, to mild injury, to significant injury and disability.

Table 4: Total Lumbar Spine Injuries Among 39 Study Subjects

Injury Type	No. of Subjects With Injury (% of Total Subjects)
Vertebral body compression fracture	7 (18)
L5-S1 symptomatic disk bulge	4 (10)
Other symptomatic disk bulges	4 (10)
L5-S1 HNP	3 (8)
L4-5 HNP	2 (5)
Transverse process fracture	2 (5)

Table 5: Surgical Treatment Among 39 Subjects

Treatment Type	No. of Subjects Undergoing Treatment (% of Total Subjects*)
C5-6 ACDF	11 (28)
C6-7 ACDF	11 (28)
L5-S1 laminectomy and diskectomy	2 (5)
C2-3 arthrodesis	1 (3)
Decompression L4-S1	1 (3)
L4-5 laminotomy, foraminotomy, and diskectomy	1 (3)

Abbreviation: ACDF, anterior cervical diskectomy fusion.
*Some subjects underwent more than 1 surgery, but revisions were not included in the tally.

CONCLUSIONS

The results of the present study show the problems inherent in the use of peak head acceleration levels as a means of determining the probability of significant spine injury following low-level accelerations. Although the significant injury rate was quite low (1 in 7700 to 16,700 riders were injured), there are several important differences between the average roller coaster rider and the average occupant in a rear-impact collision that suggest a much higher injury rate for real-world motor vehicle crashes.

The riders of the roller coaster in the present study all passed by a sign that warned them against riding if they had spine problems. All of the subjects on the roller coaster voluntarily elected to be exposed to the accelerations, and all of them were aware of the impending accelerations. None of the riders were likely to have been exposed to more than 5 or 6*g* of peak head acceleration. In contrast, occupants exposed to real-world rear-impact collisions are typically not prepared for the acceleration, and do not have the opportunity to elect out of the sudden acceleration. Real-world crash victims represent a random sampling of the population; roller coaster riders are more likely to be healthy and young risk takers. Experimental rear-impact no-damage collisions have been shown to produce more than 15*g* peak head acceleration, more than 3 times the amount of peak head acceleration measured on the roller coaster.[22] Based on the results of this study, it is apparent that in a susceptible subset of the relatively healthy general population, significant spinal injury can result from low-level accelerations.

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