Beyond the Track II: A Biomechanical Perspective on Roller Coaster Injury Risks and Recommendations for Improvement

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Abstract

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Background Context on Forces and Injury Biomechanics Research

Roller coasters exert a combination of lateral, vertical, and longitudinal forces on the human body. The field of biomechanics reveals that three basic features of these forces on riders can contribute to injury. These features include “(a) the acceleration magnitude, (b) the principal acceleration direction, and (c) the time interval over which each significant acceleration occurs” (Smith and Meaney 1118). The proportional importance of each acceleration component might fluctuate throughout the ride. Furthermore, the length of time that these accelerations are used can change significantly within the ride experience of a given roller coaster. El Toro at Six Flags Great Adventure offers a pertinent perspective to these differing force features. The first half of the ride subjects guests to large accelerations in a constant direction over a long duration in an “Out and Back” segment, whereas during the second half of the ride, riders experience short accelerations with many changes in direction over a short period of time, in what is known as a “Twister” section.

The underlying principles of injury biomechanics research relate to how the body reacts to the aforementioned forces. The amount of energy applied and the physiological area of contact are key factors in determining injury outcomes. During a roller coaster ride, force is exerted on the body due to the inertial resistance of body tissues as well as elastic and viscous compliance of the body structures (e.g., the fibrocartilaginous joints in the spine). Viscoelastic tissues of the human body absorb energy and shield essential organs from the impacts of forces (Taunton et al.). When the force applied by a roller coaster exceeds the threshold of these tissues, injuries can result.
**Risk of Brain Injury**

The hypothesis that high G force roller coasters can cause brain injury in riders has received a great deal of coverage by national mass media. “In the general press, news reports have described the perils of riding high-powered roller coasters, such as stories from the *Los Angeles Times*, ‘As thrills increase, risks to brain rise’” (Smith and Meaney 1117). In contrast to this popular conception, biomechanics researchers have noted that it “...is far too simplistic to use the G’s alone as a measure for the risk of brain injury. For example, 5-9 G’s is thought to be the maximum exposure limit for a human based on the tolerance of fighter pilots exposed to high G’s. Yet, this threshold is for sustained G’s over many seconds (mean of 43 sec), which will cause unconsciousness from reduced blood flow to the brain” (Smith and Meaney 1118). Unlike fighter jets, roller coasters tend to only impart short accelerations that typically occur in three-second increments. Moreover, these accelerations occur in several directions during the ride, with minimal probability of producing unconsciousness due to blood pooling in the extremities. Roller coaster elements that have the strongest possibility of negatively affecting the body are sustained elements, because they subject the same part of the body to a force for a long amount of time (e.g., Nitro’s double Helix). Yet, even these scenarios are not dangerous, as the amount of G force felt on the rider is controlled due to heartlining. More information about the concept of heartlining will be explored later in this paper.

An element that used to exert too much force on riders over a long period of time was the first turn on Intimidator 305 at Kings Island. During its first operating season, riders were subjected to a long, low-to-the-ground banking turn, which was ultimately reprofiled to ascend from the ground earlier. With this modification, the vertical force on riders would be shorter. Riders were concerned because many people would black out during this first part of the ride. Granted, all riders would be awake before the end of the coaster. However, this brings up the public’s concern of blacking out on roller coasters, and the severity of such an issue. Blacking out happens when the blood in the rider’s head rushes to their feet, and the brain temporarily does not have the oxygen needed to function at full capacity. This occurs during sections of rides with strong positive vertical forces, like I305’s first turn, or a long valley after the descent from Kingda Ka’s top hat. A rider will possibly lose consciousness and vision for a few seconds, but will soon be awake and able to see, as intense vertical forces should never be sustained for more than a few seconds in roller coaster design. This is where I305’s problem initially laid. On the opposite end of the spectrum is redding out, a phenomenon where the blood rushes to the head instead of away from it. The rider’s vision will become red for a moment, and this would most likely occur during moments with strong negative vertical forces (“airtime”), like Steel Vengeance’s long outerbanked hill. Fainting or passing out in a non-roller-coaster-related-scenario is caused by reactions of serious fear or shock, which causes blood pressure to drop and keeps the body from
functioning properly for a moment. Yet, people who faint will wake up in a few moments. Blacking out or redding out on a roller coaster is less dangerous than fainting from standing: the person is going to wake up in both scenarios, and one will not fall down as the result of a roller coaster blackout because they are already sitting in a roller coaster seat.

In reality, head acceleration during roller coaster rides – as opposed to strictly G forces – can contribute to brain injury. Fortunately, most roller coasters do not achieve such high acceleration levels of concern. It is important to note, however, that this assertion applies in the context of healthy individuals. “Some case reports have described rupture of pre-existing vascular malformations in the brains of roller coaster riders” (Smith and Meaney 1119). This emphasizes the importance of the safety signs outside of attractions, and why guests with pre-existing brain conditions should take caution before riding. Aside from this caveat, researchers have discovered that the maximum projected peak head accelerations caused by roller coasters were far lower than typical values that are expected to cause brain injuries, even under the most cautious analyses. The tearing of parasagittal bridging veins that may result in internal bleeding in the brain typically require a minimum head rotational acceleration of 4,500 rad/sec² (Lowenhielm). While Lowenheilm states that this acceleration is over nine times the highest accelerations that tend to occur during roller coaster rides, the below calculations reveal that 4,500 rad/sec² is even greater than 9 times the highest angular accelerations felt on roller coasters. To put angular acceleration into perspective, a segment of Intimidator 305 at Kings Dominion can be used. As one of the most forceful coasters on the planet, the ride has a bank switch that yanks riders from 80 degrees on their left side to 80 degrees on their right in a fraction of a second.

Figure 1: Intimidator 305 Bank Switch.
The angular acceleration a rider undergoes is calculated in Figure 1, based on the train taking 0.815\(^1\) seconds to complete the maneuver. It is found that the riders in the back car would undergo an angular acceleration of 8.41 rad/s\(^2\) during this forceful maneuver, 1/535 of the acceleration that tears parasagittal bridging veins. To reach 4,500 rad/s\(^2\), the maneuver would need to be taken in 0.0352 seconds: 23 times faster than the usual 0.815 seconds. This makes sense because in car crashes, for example, the neck will go from stationary to a different angle in far less than a tenth of a second, which is how these veins can actually get torn.

One of the main reasons why roller coasters tend to not result in brain injury for riders is due to the human body’s ability to diffuse G forces. “Actual head accelerations of human riders are likely to be lower than peak estimates due to dissipation of the G’s through the body and by cervical spine articulation” (Smith and Meaney 1118). Essentially, the spine moves involuntarily to minimize the abrupt movements of the head. Hence, having “wiggle room” wherein the rider’s back is set against the coaster’s seat is beneficial to not only the spines of riders, but their heads as well. Furthermore, the brain’s oxygen uptake does not tend to significantly change – unless a person has a severe underlying medical condition. In general, oxygen transport to the brain is highly preserved under gravitational pressures. The efficient autoregulation of blood flow, changes in hydrostatic pressure in the cerebrospinal fluid, and the functional properties of the intracranial veins all work together to reduce the effects of gravity during postural changes and acceleration of roller coaster rides (Blomqvist and Stone 59).

**Risk of Spinal Injury**

A human lumbar spine of the lower back has evolved over many centuries to allow for weight bearing properties, however it has limited mobility compared to other segments of the spine. Due to its relative inflexibility, injuries are more likely to occur in this region. “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%)” (Freeman et al.). An important element of roller coaster design that can reduce harm to the lower spine occurs in a process called heartlining. When a roller coaster twists for an inversion or a bank, the track should twist about an axis point centered at the rider’s heart, as opposed to having the rider pivot around an axis of rotation centered about the track. On a heartlined turn, when compared to a non heartlined turn, the body will undergo the same amount of rotational motion. Yet, on a non-heartlined turn, both the spine and the

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\(^1\) The time was found by studying an offride video at 25% speed. A stopwatch timed how long it took the rear car to travel from point A to point B. That time was divided by 4 because the video was slowed down.
head will undergo a more abrupt linear acceleration, as their radius from the point of pivot would be greater.

Another mathematical explanation for the heartlining phenomenon being less forceful on the body involves torque. Torque is a measure of the force that can cause an object to rotate about an axis, and is found using the equation $T = I\alpha$. The $I$ is calculated with different equations based on the distribution of mass. To simplify, calculating the moment of inertia for a non-heartlined turn would be like calculating the $I$ for a rod rotated about its end. Alternately, calculating the moment of inertia for a heartlined turn would be like calculating the $I$ for a rod rotated about its center. For the latter, if mass and length of the rod is kept constant, the $I$ is four times less than that of the rod rotated about its end (the non-heartlined turn). Since the angular acceleration is kept constant, the non-heartlined turn exerts four times the amount of torque on the person than the heartlined turn.

![Diagram of body's rotation on a heartlined turn and a non-heartlined turn](image)

*Figure 2: A visual explanation of the effects of heartlining on a rider.*

Unfortunately, conditions such as cervical radiculopathy and lumbar radiculopathy – more commonly known as ‘pinched nerves’ – can result from riding certain roller coasters. Cervical radiculopathy occurs when “…a nerve in the neck is irritated at the point where it leaves the spinal canal and is most commonly due to a bone spur or disc herniation. Lumbar radiculopathy develops in the same way, and involves a nerve root in the low back. Usually, it happens when a herniated disc or a bone spur pinches a nerve root” (UCLA Health Staff). There are several negative health effects that may occur from roller coaster-induced cervical and lumbar radiculopathy. They can range from minor to extensive depending on the severity of the injury. These symptoms can include loss of reflexes as well
as tingling in the neck and arm or back and leg (UCLA Health). When the neck and back are forced into unnatural postures by roller coasters, these symptoms may become worse.

To negate the possibility of pinched nerves, an example of a roller coaster that effectively positions the rider in an unnatural position is Tron Lightcycle Power Run at Shanghai Disneyland. The ride seating has guests on their knees and stomach, leaning forward in a motorbike position. There is a seatback pad that lowers down once riders are comfortable, and this pad both secures guests in place while also providing ample “wiggle room.” Hence, the risk of cervical and lumbar radiculopathy are not high even in this unusual position. Superman: Ultimate Flight is a Bolliger and Mabillard flying coaster that also effectively arranges the rider’s body in an unnatural – though generally comfortable – position while maintaining rider security and space. One caveat occurs when riders must wait for another train to board in the station or remain stationary on the break run. During these circumstances, the train remains in a horizontal “flying” position that can grow uncomfortable since riders are left on their stomachs for an extended period of time. An ergonomic improvement to the ride would be to allow the seats to lower to a sitting position on the break run.

A nineteen-month-long study was conducted by Michelle D. Freeman between the years of 1992 and 1993 which tracked the injury incident records and emergency medical service records for the Rattler wooden coaster at Six Flags Fiesta Texas in San Antonio. Of the 656 neck and back injuries caused by this single coaster during the time, 39 were considered significant by the study’s criteria. The conclusion between all the injuries deemed significant was that there seems to be no known minimal threshold for serious spinal damage due to riding roller coasters, as it can vary from person to person (Freeman et al.). A common issue with the Rattler that may have caused so many injured riders was its relentlessly bumpy drop, and its unabated triple helix, in which persistent lateral forces were exerted on riders in the same direction for 46 seconds. Fortunately, there are aspects of human anatomy that can limit spinal damage caused by roller coasters. Each individual lumbar spinal segment is composed of intervertebral discs. These discs are called fibrocartilaginous joints, and are formed of three components: the annulus fibrosus, the nucleus pulposus, and the vertebral endplates.

![Figure 3: A cross-section of the human spine](image-url)
These three components allow for mobility, shock absorption, and load distribution properties in a healthy lumbar spine (Physiopia Sta). The nucleus pulposus, a highly hydrated component, has jelly-like collagen fibers. These fibers can act as shock absorbers and help prevent roller coaster injuries. Moreover, the annulus fibrosus, end-plate cartilage, and other disc elements may raise the nucleus pulposus’ intradiscal pressure in order to sustain axial spinal stresses on riders (Physiopia Staff).

**Recommendations for Improvement**

To more accurately identify specific regions of the human anatomy that could be negatively impacted by roller coasters, extensive biomechanical testing should be conducted both before a coaster opens to the public and at frequent intervals during its period of operation. This testing can take the form of anthropomorphic test devices (ATDs) – commonly known as test dummies (Sharma et al.). The ATDs proposed in this paper refer to highly accurate mechanisms that assess the risk of human harm during a roller coaster ride. The ATDs used on roller coasters should consist of varying sizes and body types to account for the diverse demographics of riders. It is especially important to include child, teen, and adult-sized ATDs in such tests.

Furthermore, these ATDs can be improved by incorporating wearable technology that accounts for advanced principles of biomechanics related to the anatomical areas of concern referenced previously – especially the spine. The technology attached to ATDs can determine where there are gaps in ride safety standards (Sicat). These areas of concern can then be addressed by roller coaster manufacturing designs to mitigate riders’ risk of injury.

In terms of design that would negate damage to the body, sustained elements should be carefully considered during profiling, seats should have a degree of wiggle room, and turns and rolls should be heartlined as often as possible.
Works Cited


