

# Acceleration-Deceleration Sport-Related Concussion: The Gravity of It All

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**Objective:** To discuss a newtonian physics model for understanding and calculating acceleration-deceleration forces found in sport-related cerebral concussions and to describe potential applications of this formula, including (1) an attempt to measure the forces applied to the brain during acceleration-deceleration injuries, (2) a method of accruing objective data regarding these forces, and (3) use of these data to predict functional outcome, such as neurocognitive status, recovery curves, and return to play.

**Background:** Mild concussion in sports has gained considerable attention in the last decade. Athletic trainers and team physicians have attempted to limit negative outcomes by gaining a better understanding of the mechanisms and severity of mild head injuries and by developing meaningful return-to-play

criteria. Mild head injury in sports has become an even greater area of focus and concern, given the negative neurobehavioral outcomes experienced by several recent high-profile professional athletes who sustained repeated concussions. Applying the principles of physics to characterize injury types, injury severity, and outcomes may further our development of better concussion management techniques and prevention strategies.

**Description:** We describe the search for models to explain neuronal injury secondary to concussion and provide an exploratory method for quantifying acceleration-deceleration forces and their relationship to severity of mild head injury. Implications for injury prevention and reduction of morbidity are also considered.

**Key Words:** mild head injury, physics, athletic injury, axonal injury, whiplash

It has been more than 20 years since the epidemic of mild head injury and the associated medical, social, psychological, and economic consequences were first documented in the scientific literature.<sup>1</sup> Before that time, mild head trauma was considered little more than an inconvenience or nuisance to the health care community. Poor outcomes from mild head injury were attributed to conversion disorders (wherein physical symptoms or deficits that imply a neurologic or medical problem have psychological factors as a basis), depression, or other psychological overreactions to an apparently minor, transient injury. This limited understanding of the mechanism and sequelae of mild head injury was challenged in the late 1970s and early 1980s by Rimel et al,<sup>1</sup> Barth et al,<sup>2</sup> and Gronwall and Wrightson.<sup>3,4</sup> Their research revealed that some of these mild injuries resulted in impaired neurocognitive functioning that persisted for 1 to 3 months after trauma and caused slower-than-expected return to work.

Concurrent with early findings of poor outcome after mild head injury, other investigators designed animal studies to detect the presence of gross neuropathologic and histologic indications of disrupted brain functioning. Gennarelli et al<sup>5</sup> developed and used an animal model of injury analogous to the whiplash-type injury experienced by patients with mild head injuries involved in automobile crashes. In their model, a mild cerebral injury could be administered to an animal without direct impact to the skull using acceleration-deceleration forces. Microscopic examination of brain tissue from primates exposed to this experimental model revealed axonal shear strain

on autopsy. Shear strain injury is observed as the tearing or stretching of axons, which is frequently not detected in patients with mild head injuries using gross neuroimaging techniques, such as magnetic resonance imaging or computed tomographic scans. Although its focus was on the neuropathologic impact that resulted from linear forces on the brain, the research of Gennarelli et al<sup>5</sup> was instrumental in documenting cerebral injury from an apparently mild nonimpact head injury.

## SPORTS AS A LABORATORY ASSESSMENT MODEL

The aforementioned studies suggested a link between mild head injury and poor cognitive, psychosocial, and neurologic outcomes in some patients, but they raised even more questions regarding mechanism of injury (impact versus nonimpact, linear versus rotational), associated neurophysiology, and individual vulnerability. Additionally, neurocognitive deficits associated with mild head injury are often subtle, and there are tremendous differences in individual abilities. Therefore, the need to control for preinjury functioning and ability became apparent as a way of determining who is most vulnerable to a poor outcome from mild head injury. In addition, questions arose about the length of the typical recovery curve for most people. In an attempt to answer these questions, Barth et al<sup>6</sup> and Macciocchi et al<sup>7</sup> at the University of Virginia developed the Sports as a Laboratory Assessment Model (SLAM)

and published the first studies of the neuropsychological sequelae of mild acceleration-deceleration cerebral concussion in college football players. In this model, entire sports teams undergo baseline preseason neuropsychological assessment, which addresses preinjury functioning. When a player sustains a concussion during the natural course of play, he or she is reassessed, along with a matched and uninjured player, to control for practice effects due to additional testing. Next, subsequent serial assessment allows for tracking of the recovery curve. The research of Barth et al<sup>6</sup> and Macciocchi et al<sup>7</sup> revealed that all football players who sustained a concussion recovered to the performance of uninjured controls within 5 to 10 days after injury.

Even though the aforementioned research and studies by Levin et al,<sup>8</sup> Dikmen et al,<sup>9</sup> Ruff et al,<sup>10</sup> and others focused on understanding the clinical consequences of mild head injury in the general public, the sports medicine community began to take notice of SLAM as a means of studying concussion in athletes. In conjunction with professional experience, opinion, and consensus, Cantu,<sup>11</sup> Kelly et al,<sup>12</sup> and others used these data as a point of reference in the development of guidelines for return to play in an attempt to protect athletes from possible catastrophic injury related to multiple subconcussive blows and second-impact syndrome.<sup>13</sup> These data served as the foundation for further explorations into objectively understanding and evaluating sport-related head injury.

As a result of athletes' strong desire to compete and return to play, there is a tendency within the sports community to minimize the seriousness of injuries. In this context, mild head trauma has long been viewed as inconsequential because the forces exerted on the brain were deemed insufficient to cause significant neurophysiologic damage. Even under conditions in which there is no overt impact, trauma to the brain is possible. Trauma can result from a rapid change in the head's velocity or change in vector speed over time. Change in velocity over time is defined as acceleration or deceleration. Significant force, in the absence of direct and visible impact to the head, can have a detrimental effect on brain tissue. The newtonian laws of physics yield a model for potentially understanding the "gravity" of these forces on the brain. Through greater understanding and application of physics (biomechanical) principles, we may eventually develop more objective and predictive models for evaluating the immediate and long-term effects of forces exerted on the brain in the sports arena.

## LAWS OF MOTION AND MECHANICS OF INJURY

To explain the mechanism of acceleration with rapid deceleration in clinical aspects of mild head injury, Varney and Roberts<sup>14</sup> suggested applying fundamental newtonian formulas to the description of linear and rotational vector forces on the head and brain. These formulas can assist in calculating the stresses and energy displacement on neural fibers under various conditions, such as motor vehicle crashes. Severity of head injury, measured as the force of acceleration and deceleration, can be determined from such analyses. In turn, calculations can be made with regard to the potential for neurocognitive impairment. Barth et al<sup>15</sup> suggested that this newtonian physics approach be applied to the measurement of sport-related acceleration-deceleration head injury to add to our understanding of injury severity.

Deceleration, which must necessarily follow acceleration, is

the key issue when discussing the forces applied in mild concussion. Deceleration can be viewed as negative acceleration or decreasing velocity over time. The formula for calculating acceleration or deceleration is as follows:

$$a = (v^2 - v_o^2)/2sg$$

In this formula,  $a$  is acceleration or deceleration,  $v_o$  is initial speed in a given direction before deceleration starts,  $v$  is the directional speed at the end of deceleration, and  $s$  is the distance traveled during deceleration. The use of  $g$  in this formula allows for the expression of results in terms of multiples of acceleration due to gravity or  $g$  force. One  $g$  force is equivalent to 9.812 m/s<sup>2</sup> (10.73 yd/s<sup>2</sup>). Since  $v$  in a sports acceleration-deceleration model is generally calculated as 0, because the player is presumably brought to a halt, the formula can be simplified to the following:

$$a = -v_o^2/2sg$$

A real example of the application of this formula could be gleaned from game film of any contact sport, including football, soccer, lacrosse, wrestling, and equestrian sports (eg, contact with the ground, a branch, or a fence post) having high prevalence of mild traumatic brain injury. Using these films, velocity (directional speed) and stopping distances can be calculated. For instance, if a running back is traveling at 3.658 m/s (4 yd/s) and his head is brought to a stop in a distance of 0.152 m (6 in or 0.167 yd) (both of which are realistic and, in fact, conservative), the following deceleration would be calculated:

$$a = (-4)^2/(2)(0.167)(10.73) = 4.46g$$

In this hypothetical yet realistic case, the formula yields the player's velocity change over time as 4.46g, or more than 4 times the normal acceleration due to gravity, which is 1g. The force on any part of the player's mass ( $m$ ), which experiences an acceleration of magnitude ( $a$ ) (regardless of whether  $a$  is positive, reflecting acceleration, or negative, reflecting deceleration) is given by the Newton Second Law of Motion:

$$F = ma$$

If  $a$  is nothing but the acceleration of gravity, 1g, or, for example, a player falling to the ground with no other forces affecting him or her, the Newton Law gives the following:

$$F = mg$$

For example, if the player experiences an acceleration of 10g, the force on any element of mass, for example the brain, is  $F = (m)(10g)$ . Therefore, the body element experiences 10 times the force of what it would experience from gravity. Just how much  $g$  force on the brain would cause irreparable damage depends on many additional factors, as we discuss throughout this article (the study of these issues is referred to as biomechanics). Although acceleration of 30g or greater is frequently calculated in motor vehicle crashes that cause irreparable brain injury, what remains to be established is whether repeated exposure to forces of magnitude around 10g is cumulative and ultimately leads to permanent brain damage.

If the earlier value of the acceleration is inserted into the Newton Law, the Law then reads as follows:

$$F = mv^2/2s$$

This equation highlights the fact that if several different collisions occur all with the same initial speed ( $v$ ), then the smaller the stopping distance ( $s$ ), the larger the resulting force on the brain. Thus, if a player should crash into an almost immovable object, such as a goalpost or the ground, the value of  $s$  would be very small and the potential injury more severe.

We have yet to confirm what magnitude of force has significant adverse effects on the brain. An additional complication is that there are often numerous directions, or vectors, of force that might influence outcome. The simplest cases involve linear deceleration, commonly consisting of head-on or angled impacts. In the head-on variety, both players quickly experience deceleration, particularly if they are running at the same speed and have approximately the same mass. If they collide helmet to helmet or shoulder to shoulder, they are likely to decelerate very rapidly; hence, greater force is applied, and the probability of neurologic injury is higher. In this same situation, if one player's upper body collides with the other player's lower body, both athletes have longer deceleration distances and times, reducing the applied force on the brain. In the case of the angled impacts, deceleration distances and times are usually longer; thus, injury severity will likely be less. It is important to note, however, that angular impacts can cause rotational forces on the brain, which, if severe enough, can result in several rapid changes in velocity (directional speed) over short distances, periods, or both.

Countless scenarios exist for acceleration-deceleration injuries in sports. The aforementioned scenarios assume that both players are anticipating the collision and are prepared. If unaware of an impending impact, players may fail to appropriately align their bodies or tense their neck muscles. In such cases, players may experience a whiplash-type force. This creates torque, seen as rotation of the head either in or out of its original plane. When changes in velocity (acceleration) are dramatic and occur over short distances, the outcomes are more negative than those in injuries that result from linear impacts.

Acceleration-deceleration, by definition, implies a particular direction or vector. Changes in the vector of acceleration or deceleration (ie, rotational or twisting forces) further complicate the computation of the sum of forces brought to bear on the brain. In other words, whether the brain is "torqued" in a rotational fashion has considerable influence on functional outcome. Consider "clotheslining," which can occur as a result of player-to-player contact in some contact sports. In this instance, the head does not merely decelerate in unidirectional fashion but is actually decelerating in the original vector and accelerating in a new vector, usually rotating backward and downward. Multiple vectors of acceleration and deceleration in response to forces applied to the brain likely account for the greatest histokinetic changes, or axonal injuries, in mild head injury. These likely lead to the greatest impairments in neurobehavioral outcome.

It is also important to note that the brain is at risk for damage at numerous points. In the linear case, sufficient force in the opposite velocity vector may cause the brain to strike against the inner skull in the direction it was initially traveling (coup injury). Additionally, the brain may "rebound" from the

direction of the deceleration and strike the inner lining of the skull in the opposite direction (contrecoup injury). With rotational force, the sites in which the brain may contact or scrape the inner lining of the skull become manifold. Although no true coup or contrecoup injury may exist, the magnitude of tissue alteration (ie, shear strain injury and diffuse axonal injury) can be significantly larger when significant rotational forces are applied to the brain.

## USING NEWTON TO PROTECT THE ATHLETE

Physics formulas for calculating acceleration-deceleration and forces applied to the head also have implications for the prevention of and protection against serious injury. Both the time and the distance over which changes in velocity occur influence outcome. For instance, the cushioning effect of helmets increases the distance of deceleration and reduces the forces associated with these injuries. Helmets also increase the surface area across which the blow, or force, is absorbed. This is evident in another newtonian formula, wherein  $P$  refers to pressure,  $F$  indicates the force applied, and  $A$  is the area to which the force is applied:  $P = F/A$ . By distributing the applied force to the helmet from an impact with another helmet, body part, or the ground, the pressure exerted on the head is actually decreased as a function of the area of the helmet.

Winters<sup>16</sup> reports on the value of properly fitted mouthguards, which may reduce the severity and incidence of cerebral concussion for specific mechanisms of injury. Using the physics model, the cushioning effects of a properly fitted mouthguard, particularly during a linear impact that involves the mandible, increase the time and distance of deceleration and likely offer cerebral protection. Enforcement of rules against spearing (using the head to tackle) is another clear strategy that also helps to increase deceleration distance. When a player's first contact is against the body of an opponent, the head has more distance for any changes in velocity. Proper training to prepare for contact on the sports field is also essential, since unexpected blows or changes in velocity of the head can produce the greatest forces on the brain. In soccer, properly tensing the muscles of the back and neck in preparation to head a ball disperses the area across which the force is applied. The head, neck, and upper torso are, therefore, used in unison to absorb the impact of the ball on the head, resulting in decreased velocity change for the head itself. This principle is easily extended to training athletes in the rules and techniques of tackling or checking, specifically, how to absorb these blows through anticipation and preparation of the entire body.

## FUTURE DIRECTIONS

Use of the aforementioned formulas provides a good conceptual basis for understanding the mechanics of forces applied to the brain during sport-related concussion. Additionally, these formulas have pragmatic uses as well. Today's video technology allows for minute discriminations between distances and times. In the sport setting, analysis of game films thus permits computation of player velocity before impact and the deceleration value. Factoring in player mass, computing an estimate of the force of impact is then a reasonable endeavor. A database that tracks mechanism of injury (eg, head to head, head to body, head to ground, head to goalpost), estimated force of impact, and resultant functional outcome mea-

sures (eg, loss of consciousness, altered consciousness, neurologic and neuropsychological signs and symptoms) is then attainable. A history of head injury and the estimated magnitude of the force involved are also important factors that allow us to begin to examine the effect of repeated exposures to small force impacts.

Clearly, the analysis of the force applied specifically to the head is more complicated than we have suggested herein, since it necessitates consideration of all vectors involved in the impact. However, moviegoers will note that technologies can now create a freeze-frame rotation around a particular scene. Although few cameras are used, computer-generated images are inserted to fill the gaps. Applying this technique to the game or practice setting may enable coaches, athletic trainers, and other medical personnel to analyze game films and examine the direction of the forces applied to the head. Although such an evaluation is seemingly complex, perhaps it will not be too far in the future when such images will be both generated and analyzed by these programs, yielding more refined measurement of these forces and enhancing our understanding of the mechanics of mild head injury in sports.

## REFERENCES

1. Rimel RW, Giordani B, Barth JT, Boll TJ, Jane JA. Disability caused by minor head injury. *Neurosurgery*. 1981;9:221–228.
2. Barth JT, Macciocchi SN, Giordani B, Rimel R, Jane JA, Boll TJ. Neuropsychological sequelae of minor head injury. *Neurosurgery*. 1983;13:529–533.
3. Gronwall D, Wrightson P. Delayed recovery of intellectual function after minor head injury. *Lancet*. 1974;2:605–609.
4. Gronwall D, Wrightson P. Cumulative effect of concussion. *Lancet*. 1975;2:995–997.
5. Gennarelli TA, Adams JH, Graham DI. Acceleration induced head injury in the monkey. I: the model, its mechanical and physiological correlates. *Acta Neuropathol (Berlin)* 1981;1(suppl):23–25.
6. Barth JT, Alves WM, Ryan TV, et al. Mild head injury in sports: neuropsychological sequelae and recovery of function. In: Levin HS, Eisenberg HM, Benton AL, eds. *Mild Head Injury*. New York, NY: Oxford University Press; 1989:257–275.
7. Macciocchi SN, Barth JT, Alves WM, Rimel RW, Jane JA. Neuropsychological functioning and recovery after mild head injury in collegiate athletes. *Neurosurgery*. 1996;39:510–514.
8. Levin HS, Mattis S, Ruff RM, et al. Neurobehavioral outcome following minor head injury: a three-center study. *J Neurosurg*. 1987;66:234–243.
9. Dikmen S, McLean A, Tempkin N. Neuropsychological and psychosocial consequences of minor head injury. *J Neurol Neurosurg Psychiatry*. 1986;49:1227–1232.
10. Ruff RM, Levin HS, Mattis S, et al. Recovery of memory after mild head injury: a three center study. In: Levin HS, Eisenberg HM, Benton AL, eds. *Mild Head Injury*. New York, NY: Oxford University Press; 1989:176–188.
11. Cantu RC. Guidelines for return to contact sports after a cerebral concussion. *Physician Sportsmed*. 1986;14(10):75–83.
12. Kelly JP, Nichols JS, Filley CM, Lillehei KO, Rubinstein D, Kleinschmidt-DeMaster BK. Concussion in sports: guidelines for the prevention of catastrophic outcome. *JAMA*. 1991;226:2867–2869.
13. Cantu RC. Second-impact syndrome. *Clin Sports Med*. 1998;17:37–44.
14. Varney NR, Roberts RJ. Forces and accelerations in car accidents and resultant brain injuries. In: Varney RN, Roberts RJ, eds. *The Evaluation and Treatment of Mild Traumatic Brain Injury*. Mahwah, NJ: L Erlbaum; 1999:39–47.
15. Barth JT, Varney RN, Ruchinskas RA, Francis JP. Mild head injury: the new frontier in sports medicine. In: Varney RN, Roberts RJ, eds. *The Evaluation and Treatment of Mild Traumatic Brain Injury*. Mahwah, NJ: L Erlbaum; 1999:81–98.
16. Winters JE Sr. Commentary: role of mouthguards in prevention of sport-related concussion. *J Athl Train*. 2001;36:339–340.