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Newton's Laws, G-forces and the Impact on the Brain

Zasady Newtona, siła grawitacyjna a ich wpływ na mózg

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Abstract

The thrill to go fast and push boundaries is something that many seek. From John Stapp's rocket sled at Edwards Air Force Base in the late 1950's to todays' Formula 1 drivers, the "need for speed" is broadcast across TV screens weekly. So too are the horror stories of crashes, many at over 300 km/hr. Yet "need for speed" continues. It appears that the higher and faster the rollercoaster, the better. This leads to several questions. How does the brain stand up to speed and G-forces? Do Newton's Laws still have reference in today's world?

There has been much attention in the general press on the possibility that high G-force roller-coasters are inducing brain injury in riders. However, research does not wholeheartedly support this notion, but rather the risk of brain injury from a rollercoaster is not in the rides, but in the rider — caused by previously undetected brain or neck conditions. That said there is some truth that high G-forces do affect the brain at a chemical and structural level.

This paper will discuss the mechanism of head injury at speed and generally what Newton's Law means in a neurological setting in todays' world. Formula 1 racing and rollercoaster rides will be evaluated within a neuroscience context. **(JNNN 2019;8(3):133–137)**

Key Words: concussion, head injury, Newton's laws, Formula 1

Streszczenie

Wiele osób poszukuje dreszczyku emocji związanego z szybką prędkością oraz przekraczaniem jej granic. Począwszy od sań rakietowych Johna Stappa w bazie Sił Powietrznych Edwards pod koniec lat 50. XX wieku po dzisiejszych kierowców Formuły 1, każdego tygodnia w telewizji możemy oglądać „need for speed". Oglądamy również liczne przerażające historie z wypadków, często powiązane z przekraczaniem prędkości 300 km/h. Jednak „need for speed" („potrzeba prędkości") nadal nie ustaje. Może się nam wydawać, że im wyższa i szybsza kolejka górska, tym lepiej. Rodzi to jednak kilka pytań. Jak mózg radzi sobie z prędkością oraz siłami grawitacyjnymi? Czy prawa Newtona nadal mają odniesienie w dzisiejszym świecie?

W prasie wiele uwagi poświęcono ewentualności, iż kolejki górskie o dużej sile grawitacyjnej powodują uszkodzenie mózgu u ich użytkowników. Jednak badania naukowe nie do końca popierają tę tezę, twierdząc, że przyczyna uszkodzeń mózgu nie leży bezpośrednio po stronie kolejek górskich, ale wiąże się z ich użytkownikami — twierdząc, że zostały one wywołane wcześniej niewykrytymi schorzeniami mózgu lub szyi. Jest w tym jednak trochę prawdy, że duże przeciążenia mają wpływ na mózg na poziomie chemicznym i strukturalnym. Niniejszy artykuł omawia mechanizm urazu głowy odniesiony w wyniku dużych prędkości oraz to, co ogólnie oznacza Prawo Newtona w środowisku neurologicznym w obecnych czasach. Formuła 1 oraz przejażdżki kolejkami górskimi zostaną ocenione w kontekście badań nad układem nerwowym. **(PNN 2019;8(3):133–137)**

Słowa kluczowe: wstrząśnienie mózgu, uraz głowy, Zasady Newtona, Formuła 1

Introduction

When thinking about head injury, one needs to first understand forces and the way they impact the body. Gravitational force, or G-force, is the force of gravity on a particular body — a measurement (in G's) of acceleration that causes the perception of weight. It has significant applications in scientific & engineering fields especially regarding racing cars, fighter jets, large engines and rollercoasters.

This paper will discuss the mechanism of head injury at speed and generally what Newton's Law means in a neurological setting in todays' world. Formula 1 racing and rollercoaster rides will be evaluated within a neuroscience context.

Literature review

It is interesting to note (see Table 1) that the force of gravity whilst just standing on the earth, increases markedly with a slap on the back. Then further when in a car or a rollercoaster and even more if having sustained a concussion.

Table 1. How many G's?

How many G's?	
Standing on the Earth	1 G
Rollercoasters	3.5–6.3 G
A slap on the back	4.1 G
Formula 1 Racing car	5 G
The luge at Whistler	5.2 G
'Plopping' into a chair	10.1 G
Sneezing (open mouth)	2.9 G
Concussion	80–100 G

From: Slade S.B. *Feel the G's: The Science of Gravity and G-forces (Headline Science)*, Compass Point Books, USA 2009.

In today's modern age, Sir Isaac Newton's theories and laws are still included in the curriculum taught to students at school. From his theories of optics and calculus, to his ground-breaking work on the laws of motion and gravity, which formed the basis for modern physics, he dominates the fields of science, astronomy, physics and the natural world, proving invaluable to centuries of mathematicians, engineers and scientists.

In health, the Valsalva manoeuver is a technique of force used to equalise pressure [2]. People perform the Valsalva manoeuver regularly without knowing it. For example, it is used to increase colonic pressure to induce a bowel movement and it may also be beneficial when used intentionally to try to regulate heart rhythms. It is also used when experiencing a change in altitude to help equalise the ears by forcing them to 'pop', such as when scuba diving or in aeroplanes. The main side effect of performing the Valsalva manoeuver is hypotension and resultant forces impacting intra-ocular, intra-abdominal and intra-cerebral pressure.

These forces are also produced in the acts of vomiting, coughing and sneezing. As neuroscience nurses, the knowledge regarding the impact of these forces is known to be troublesome in relation to the consequences of these forces on intra-cerebral pressure and the homeostasis of the brain. It should be kept in mind that the involuntary act of sneezing has ramifications from a G-force perspective. The act of sneezing with an open mouth has a force of 2.9 G's. Yet holding in a sneeze internally redirects the force and this can result in eye injury, ruptured ear drum, herniated nucleus pulposis (herniated disc) and throat injury [3].

Newton's First Law: (Inertia). An object will remain at rest, and an object will remain in motion, unless acted upon by an unbalanced force. For example, a fast car hits a brick wall. The car stops… but the person does not. Since an object at rest stays at rest, rollercoasters have to be pushed or pulled along the track. In this way, potential energy is stored for the entire ride. At the top, the rollercoaster is put into motion and will not stop until the brakes are applied at the end of the ride.

The world's fastest rollercoaster is the *Formula Rossa* rollercoaster in Ferrari World, Abu Dhabi, United Arab Emirates. It is 53 m high and has a maximum speed of 240 km/h via a hydraulic slingshot launch. In this way, acceleration is 0 to 240 km/h in 4 seconds. The G-force is 4.8 G, requiring the rider to wear goggles for eye protection [4].

Newton's Second Law: (Force = mass x acceleration). This law explains how the velocity of an object changes when it is subjected to an external force. This is felt when going down hills. The coaster cars and your body have mass. The gravity provides acceleration, which causes force. The rider feels the force as it moves the cars along the track. The track directs the force and the cars. In positive G's, the body feels heavier — at the bottom of the hills, turns and loops. For example, a 70 kg person at 2 G's would have the perception of 140 kg and at 3 G's it would feel like 280 kg. Whereas with negative G's, the body feels weightless — at the top of the hills.

Newton's Third Law: (Action/reaction). For every action (force), there is an equal and opposite reaction. For example, as your body is pushed down into the seat of the rollercoaster, the seat pushes back.

Newton's Laws permiate throughout engineering and science fields and are still current in today's practice. It was Dr John Stapp, a United States Air Force Colonel, flight surgeon, physician, biophysicist, and pioneer in studying the effects of acceleration and deceleration forces on humans, who put Newton's Laws to the test on the human body.

At New Mexico's Air Force Base, December 10, 1954, John Stapp was strapped into the *Sonic Wind* rocket sled. His arms and legs were secured. There was no windscreen, so he wore goggles, a mouthguard and a helmet. The sled was powered by nine solid fuel rockets and it fired and propelled him more than 3.000 feet in a few seconds. He came to an abrupt stop and experienced a force equivalent to 46.2 G. Not without injury, he walked away with the world land speed record, 632

miles/hour, which he still holds today, giving him the title of "the Fastest Man on Earth" [5]. However, the blood vessels in his eyes had burst, rendering him temporarily blind. He also sustained bilateral wrist and rib fractures.

The outcome of these experiments allowed for the development of improved pilot harnesses and aircraft seats, modern crash-test dummies, the ejection seat and high-altitude pilot suits. Stapp's research improved aircraft safety and also led to the development of the shoulder seat belt. In September 1966, President Johnson, with John Stapp present, signed the Highway Safety Act, in which it was required that all new cars, as of 1968, sold in the USA, be fitted with seat belts [6].

When thinking of acceleration, the picture that formulates is usually of a sports car doing 0 to 60 in six seconds. However, acceleration is any change in the velocity of an object — going faster, slowing down or changing direction. Therefore, on a rollercoaster, the G-forces are felt when rounding tight bends and thrown against the side of the seat (a change in direction) just as much as when falling from height (accelerate) or screeching to a stop (decelerate). The thrill is felt, but there is no fainting, because the rollercoaster was designed to be within the G-force tolerance of the average person. However, the amount of tolerable G-forces differs by individual and it also depends on several factors: the direction in which the G-forces are felt, the amount of G's involved, and how long those G's last [7].

At sea level, or 1 G, humans require 22 millimeters of mercury blood pressure to pump sufficient blood from the heart to the brain. In 2 G's, twice that pressure is needed, in 3 G's, three times, and so on. Even with a G-force of 4 or 5, the heart struggles to summon the necessary pressure. Blood pools in the lower extremities and the brain fails to be adequately oxygenated. Most people then faint.

Fighter pilots can handle greater head-to-toe G forces — up to 8 or 9 G's — and for longer periods by wearing anti-G suits. These specialised suits use air bladders to constrict the legs and abdomen during high G's to keep blood in the upper body. Fighter pilots can further increase their G-tolerance by training in centrifuges, which create artificial G's, and by learning specialised breathing and muscle-tensing techniques. Magnitude and duration of the forces are as critical as direction. Whilst John Stapp showed that people can withstand much higher G-forces than had long been thought, there is a limit to what most people can tolerate.

There is a limit to what humans can take. Tragically, Princess Diana proved that.

Princess Diana was a catastrophic example of how G-forces affect the human body. It was estimated that the G-forces on her chest were around 70 G's and 100 G's on her head. The acceleration caused a fatal tear in her pulmonary artery. If Princess Diana had been wearing a seatbelt, the G-forces would have been less and she may have lived [8].

While Formula 1 (F1) racing drivers may feel around 5-G's, under heavy braking, they can experience over 100-G's if a crash causes them to decelerate quickly over a short distance.

The weekend of May 1st 1994, during the San Marino Grand Prix, was Formula 1's worst race weekend in history. That weekend of racing in Imola, Italy, saw the death of Austrian, Roland Ratzenberger in practice and that of Brazillian, Ayrton Senna the following race day.

"God has had His hand over Formula 1 for a long time. This weekend, He took it away".

Niki Lauda — Reuters, 1994 [9]

Niki Lauda spoke these words in 1994 after Ratzenberger crashed at over 306 kph during qualifying and 24 hrs later, Senna died when his car slammed into a concrete wall at 220 kph. Both died as a result of catastrophic head injuries. Following these deaths, F1 underwent many changes from car design to fuel and tyres. There hadn't been any deaths on the F1 circuit since 1994, but that came to an end in 2015 during the Japanese Grand Prix, when 25 yr old driver Jules Bianchi crashed at 258 kph and sustained severe head injuries. He succumbed to these injuries a few months later. The G-force sensor located in his earplugs recorded a 92-G impact [9], much greater than the human body is designed to withstand.

G-forces act on blood and blood vessels. Just as they push the body into the seat, they also push the blood back away from the brain and toward the feet. Therefore, astronauts wear a pressurised G-suit that prevents blood pooling in the extremities. This is similar to anti-thrombotic stockings that can be worn for long-haul flights. If G-forces are brief, the effects on the body will be less. It is when G-forces linger, or are sustained, that causes concern. Hence, during launches of the space shuttle, controllers keep the shuttles' acceleration low — no greater than 3-G's, so as not to unduly stress the astronauts.

The eyes are especially susceptible to G-forces and some of the first signs of problems in the cockpit arise from partial loss of vision. Pilots know it as 'greyout' — greying of vision due to reduced blood flow to the eyes. This can serve as a warning of the decreased blood flow to the head. Consciousness is maintained but blood flow to the eyes is compromised. However in some

studies, half the pilots experienced unconsciousness at the same time as the loss of vision, therefore a pilot cannot rely on visual disturbances to warn them of unconsciousness.

'Blackout' or loss of consciousness occurs when cerebral blood flow is reduced. In many centrifuge studies, the pilots were amnesic to the events of losing and gaining consciousness. Symptoms may include convulsive movements and slumping in the seat. This could be dangerous if falling against the controls. However, it is an individual experience whether or not consciousness is maintained. Tolerance is related to the rate of onset of acceleration and to the duration of exposure. Individual tolerance depends on factors such as the height of the person, age, elasticity of the blood vessels, training, the responses of the heart and blood vessels, and general health. G-forces can also detach a retina.

What Do Some Animals Have that Humans Don't?

Drake et al. [10] describe that the bighorn sheep, as a part of fighting and mating, routinely experience violent impacts to the head without negative consequences to their brains or horns. Their horns consist of a bony material and a trabecular mesh-like structure which absorbs the impact that occurs during ramming. The woodpecker too has significant internal structures that absorb the impact of pecking a tree at over twenty times per second. Their secured hyoid bone, uneven beak and tight cranial cavity absorb the shock. It is from studying these two animals in particular, that the researchers have developed improved mouthguards, helmets and flight data recorder cases. The European Organisation for Civil Aviation Equipment Committee, an international body on which the Australian Transport Safety Board (ATSB) was represented, revised the standards of flight data recorders in 2003. Today, these flight data recorders are able to withstand an acceleration of 3.400 Gs (3.400 times the force of gravity) [11].

So Where Does the Literature Stand with Regard to Brain Injury and Rollercoasters?

In 2002 Smith & Meaney [12] suggested that the human body can withstand very large G-forces when they occur over very short periods of time, which is the current thought today. They suggested that the loss of consciousness is from restriction of blood flow rather than mechanical injury to the brain. Their studies illustrated that to injure the brain, there needs to be greater linear force (G's) as well as rotational force. They went on to say that neck or back injuries would be far more likely than brain injuries from rollercoasters.

Again, the thought in 2003 was that the risk of brain injury from a rollercoaster is not in the rides, but in the rider — caused by previously undetected brain conditions or spine injuries from the force in the turns [13].

Yamakami et al. [14] and Roldan-Valadez et al. [15] described anecdotal case reports of potential causal relationships of patients suffering brain bleeding around the time of riding a rollercoaster. This is now not supported by epidemiological or scientific data.

Although Roldan-Valadez et al. [15] presented a paediatric patient with a subdural haematoma, fourteen days after having ridden a rollercoaster, the causative element cannot be correlated entirely to the rollercoaster. The results are also limited as there was only one individual in this study.

Pfister, et al. [16] also agreed that it's not the ride, but the rider and said that there was an extremely low risk of TBI due to head motions induced by roller coaster rides. Similarly, Kuo et al. [17] suggested that rollercoaster rides do not present an immediate risk of acute brain injury. However, head motion and brain deformation during rollercoaster rides are highly sensitive to individual subjects — who already are predisposed to brain injury.

However, in 2018 there was a growing concern about the G-force that is exerted on people as they ride these faster rollercoasters, as the desire to go faster is ever-present. In October 2018, New Jersey, USA became the first state to limit G-forces on theme park rides.

The American Association of Neurological Surgeons has assembled a national committee of neurosurgeons, NASA scientists and engineers that are now looking at how the stress of G-forces from rollercoasters might affect the brain, specifically how the brain is bounced around inside the skull on these rides. The committee has not yet reached any conclusions [18].

Zhu et al. [19] describes the studying animals such as the barbary sheep and woodpeckers have given insight into how these animals cope with extreme force impacts. Inspired by the woodpecker's head, researchers have developed a casing for aircraft flight recorders that canwith stand a G-force of up to 60.000-G's (previously 3.400 G's).

Conclusions

Being wrapped in cottonwool is not an option. Sport and fun are synonymous. The desire to go fast is thrilling and it seems that the faster the rollercoaster, the better! Keeping a child safe is a parent's obligation and companies have that same obligation of safety. As demonstrated by Stapp in the 1950's, humans can be subjected to high G-forces and survive, as long as it is for a short duration. Magnitude and duration are as critical as direction, when it comes to forces. Safety is paramount in industries where G-forces are found — engineering, space travel,

F1 racing and theme parks. With this in mind and knowing the mechanism of injury, F1 responded with changes to car design and changes to rules and procedures following driver injury.

Rollercoasters that generate G-forces for the pursuit of fun-filled terror must be conscious of the pressure that is placed on the human body during these rides. Safety mechanisms and short duration of twists, turns and speed, must be taken into account and adapted for the safety of all.

With this knowledge of G-forces, people are better placed to judge whether or not to put their bodies through these forces. It must also be clear that if a person knows or suspects they might have a brain or neck injury, then obviously it is unwise to participate in an activity that could compromise their health. Warnings at each ride are placed for a reason, informed knowledge and decision-making as well as coverage for litigation purposes. These must be taken seriously, as it is a fine line between being well and unwell.

Implications for Nursing Practice

Neuroscience nurses play a role in teaching the public — through seminars, school educational sessions and governments and companies have an obligation for public safety. Although life is becoming a minefield of "Safe Operating Practices" and every product has a warning attached, fun activities are encouraged, just within reason. The brain, within its' hardened case, is protected but also vulnerable to changes in pressure and force. Pre-existing conditions of the brain or neck, whether known or not, plays a role in injury from rollercoasters and theme park rides. Some obligation must rest with the individual. That is, the issue remains with the rider — their health and informed decision on whether or not to ride.

References

[1] Slade S.B. *Feel the G's: The Science of Gravity and G-Forces (Headline Science)*. Compass Point Books, USA 2009.

[2] Pstras L., Thomaseth K., Waniewski J., Balzani I., Bellavere F. The Valsalva manoeuvre: physiology and clinical examples. *Acta Physiol (Oxf)*. 2016;217(2):103–119.

[3] Yang W., Sahota R.S., Das S. Snap, crackle and pop: when sneezing leads to crackling in the neck. *BMJ Case Rep*. 2018, doi: 10.1136/bcr-2016-218906.

[4] Beaudette D. Report on G-force effects on the human body. Department of Transportation, Federal Aviation Administration. National Technical Information Service. U.S. Department of Commerce, Virginia, USA: 1984.

[5] Atwell C. Extreme Motion Tests Brought Aerospace Safety Innovation. *Machine Design*. 2017.

[6] Ryan C. *Sonic Wind: The Story of John Paul Stapp and How a Renegade Doctor Became the Fastest Man on Earth. 1st Edition*. Liveright Publishing, New York 2015.

[7] Evans J. The Big Thrill, The Hidden Danger. *Prevention*. 2002;54(7):40.

[8] *Operation Paget Report — into the death of Diana Princess of Wales*. UK Metropolitan Police, 2009.

[9] Bednall J. *Jules Bianchi survived 92G impact in horror Formula One crash*. Retrieved July 17, 2019, from https://www.news.com.au/sport/motorsport/formula-one/jules-bianchi-survived-92g-impact-in-horror-formula-one-crash/news story/c381589f42393105511f8413c3b2fd52

[10] Drake A., Haut Donahue T.L., Stansloski M., Fox K., Wheatley B.B., Donahue S.W. Horn and horn core trabecular bone of bighorn sheep rams absorbs impact energy and reduces brain cavity accelerations during high impact ramming of the skull. *Acta Biomater*. 2016;44: 41–50.

[11] Australian Transport Safety Bureau — Fact Sheet. Retrieved June 21, 2019, from www.atsb.gov.au

[12] Smith D.H., Meaney D.F. Roller coasters, g forces, and brain trauma: on the wrong track? *J Neurotrauma*. 2002;19(10):1117–1120.

[13] Retrieved June 22, 2019, from https://www.biausa.org/.

[14] Yamakami I., Mine S., Yamaura A., Fukutake T. Chronic subdural haematoma after riding a roller coaster. *J Clin Neurosci*. 2005;12(1):81–83.

[15] Roldan-Valadez E., Facha M.T., Martinez-Lopez M., Herrera-Mora P. Subdural hematoma in a teenager related to roller-coaster ride. *Eur J Paediatr Neurol*. 2006;10(4): 194–196.

[16] Pfister B.J., Chickola L., Smith D.H. Head motions while riding roller coasters: implications for brain injury. *Am J Forensic Med Pathol*. 2009;30(4):339–345.

[17] Kuo C., Wu L.C., Ye P.P., Laksari K., Camarillo D.B., Kuhl E. Pilot Findings of Brain Displacements and Deformations during Roller Coaster Rides. *J Neurotrauma*. 2017;34(22):3198–3205.

[18] Retrieved July 23, 2018, from https://abcnews.go.com/

[19] Zhu Z., Zhang W., Wu C. Energy conversion in woodpecker on successive peckings and its role on anti-shock protection of brain. *Sci China Technol Sci*. 2014; 57(7):1269–1275.

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