Almost all high impact sports require some form of protective headgear. Helmets were originally introduced as sports protective equipment in 1896 when early devices were fashioned out of leather strips. A suspension system was integrated into the next evolution of these leather caps, such as the 1930s MacGregor & Goldsmith leather helmet. Contrary to the anticipated benefits of helmets, incidence of head injuries, including concussions actually increased due to prevalence of head-to-head collisions. Helmet use was voluntary until 1939 when, due to an epidemic of fatalities, the National Collegiate Athletic Association (NCAA) mandated the use of football helmets at the collegiate level. The National Football League (NFL) adopted the same requirement for professional players in 1943. During this era the football helmet evolved significantly, with the development of the first plastic shell helmet in 1937. Our athletes' current helmets include an outer shell and inner lining and are designed to absorb and disperse energy after contact. They can be designed for a single impact (i.e., bicycle helmet) or repetitive impact (football and ice hockey).

In 1969, following 38 football fatalities nationwide, the National Operating Committee on Standards for Athletic Equipment (NOCSAE) was formed to establish helmet-testing standards. Current standards involve dropping a helmet with a head form inside from a specific height and measuring linear acceleration (i.e., forces responsible for skull fracture and intracranial hemorrhage). In 1978 the NCAA and National Federation of State High School Association mandated that all players must wear helmets that meet NOCSAE test standards. Specific helmet requirements can vary by organization or sport and none of the current standards for assessing football helmet performance, or helmets for any sports application in the US, require measurement of the types of forces believed to be responsible for concussion or subdural hematoma, i.e., rotational or angular acceleration.

TRAUMATIC BRAIN INJURY

There are two primary mechanisms associated with traumatic brain injury: impact loading and impulse loading. Impact loading involves a direct blow transmitted primarily through the center of mass of the head causing linear acceleration and results in extracranial focal injuries, such as contusions, lacerations, external hematomas and skull fractures. Shock waves from blunt force trauma may also cause underlying focal brain injuries, such as cerebral contusions, subarachnoid hematomas and intracerebral hemorrhages. Impulse (inertial) loading caused by sudden movement of the brain relative to the skull results in angular and rotational acceleration and produces subdural hematomas and concussion. Inertial loading at the surface can produce bridging vein rupture and resultant subdural hematoma or can affect deep white matter structures producing diffuse axonal injury (DAI). Holbourn was the first to cite angular acceleration as an important mechanism in brain injury. Gennarelli, Thibault, and colleagues, in a series of studies using live primates and physical models investigated the role of rotational acceleration in brain injury. They concluded that angular acceleration contributes more than linear acceleration to the generation of concussive injuries, diffuse axonal injuries, and subdural hematomas.

THRESHOLDS

While there is scientific consensus that forces associated with angular/rotational acceleration of the brain are the accepted mechanism for concussion, there is still no consensus on concussion threshold. Some continue to suggest thresholds based on linear accelerations. Ono published a summary of research regarding thresholds for human skull fracture based on cadaver experiments. The heads were suspended, while a series of 42 frontal, 36 occipital and 58 temporal blows were delivered, during which linear accelerations...
tions were measured. Frontal and occipital impacts shared a skull fracture threshold of 250g for a 3 meters per second (msec) impact duration, decreasing to 140g for a 7msec impact duration. While skull fracture threshold for lateral impacts was 120g over 3 msec duration, decreasing to 90g for a 7msec duration. Results clearly indicate that skull fracture threshold is inversely related to impact duration.

At present there is no accepted threshold (i.e., angular and rotational) for concussion. Several studies have been performed toward identifying thresholds for concussion. Ommaya and Gennarelli published a landmark study on cerebral concussion and traumatic unconsciousness in 1974. The researchers devised an inertial loading apparatus that produced pure translational (linear) or rotational (angular) loading on the heads of primates without inducing contact phenomena (impact). Pure translation produced focal injuries, such as contusions, while diffuse effects, including concussion and subdural hematoma were only produced when the rotational loading was present. Pellman and colleagues published a series of studies in which they performed biomechanical reconstructions of concussive impacts during NFL football games. The researchers reported that concussions were related to linear and rotational accelerations in the order of 98 ± 28g and 6432 ± 1813 rad/s², respectively, while sub-concussive impacts averaged 57 ± 22 g and 4029 ± 1438 rad/s². Their results show that a concussion is possible at 45g / 3500 rad/s², while 5500 rad/s² represented a 50 percent risk of concussive trauma.

Rowson and Duma have published extensively on their laboratory and field-based biomechanical evaluations of head injuries in football. Their findings are based on a large database of football impacts recorded by a Head Impact Telemetry System (HITS), developed by Simbex, Inc. (Lebanon, NH), which incorporates an array of uni-axial accelerometers in the crown of a player’s helmet. Based on 62,974 recordings of sub-concussive impacts and 37 diagnosed concussions, a concussion threshold of 104 ± 30g and 4726 ± 1931 rad/s² was computed. A significant value in this research comes from the identification of thresholds for sub-concussive impacts, the cumulative effects of which some believe to be highly correlated with early onset of cognitive dementias. The top 50% of sub-concussive impacts in the HITS dataset consisted of impacts with average accelerations of 38 ± 20 g and 1528 ± 984 rad/s², while the top 25% of sub-concussive impacts consisted of impacts with average accelerations of 52 ± 21 g and 2036 ± 1124 rad/s². It should be noted that the thresholds for concussive impacts calculated by Pellman and Rowson exceed scientific consensus of thresholds for subdural hematoma in football impacts.

Studies by Lowenhielm, who performed mechanical tests on human cadavers, concluded that bridging vein rupture then the epidemiologic data should reflect an appreciable risk of subdural hematoma associated with head impacts resulting in angular accelerations of 5,000 rad/s². If Pellman’s and Rowson’s data were correct, concussion threshold greater than those required for bridging vein rupture then the epidemiologic data should reflect an epidemic of subdural hematomas, which of course is not the case. Therefore, one must seriously question the validity of the findings of these studies.

**THE LIMITATIONS OF HELMETS**

Current biomechanical data (there are no true clinical studies) suggests that helmets do an adequate job in protecting against serious head injury, however are quite limited in protecting against concussion. Why? Helmets and their underlying padded material both absorb and spread forces over a greater surface area when compared to the unprotected head. However, they have little ability to decrease rotational and angular acceleration. The brain is a free floating structure with little resistant and deforms easily especially when rotational and angular forces are applied directly the head or transmitted from the torso. The only true way to clinically reduce angular and rotational acceleration in to immobilize the cervical spine.

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dropped from the 48 and 60 inch height for fear of damaging the head form) with four impact locations i.e., frontal, temporal, occipital and vertex. During linear acceleration (they did not measure rotational or angular). Helmets were rated from 1 to 5 stars based on the average peak acceleration (three drops per helmet, 2 trials, 20 tests per helmet).

In their analysis the authors hypothesized that lowering linear acceleration will lower rotational acceleration and thus reduce concussion. The Riddell Revolution Speed was the only helmet receiving 5 stars, the Adams A2000 Pro Elite received 0 stars, five other helmets received 4 stars. The leather helmets failed to outperform any of the helmets in peak acceleration.

Our group has performed the most comprehensive analysis of all current football helmets on the market as well as helmets currently used by high school and other amateur leagues (no longer manufactured). A total of 21 modern helmets and a 1930’s Goldsmith leatherhead were tested. Unlike the studies above and the NOCSAE testing, we used a modified drop test apparatus that is able to induce and directly measure linear and rotational acceleration. Using the concussion threshold set forth by Ommaya (3000 rad/s²) and skull fracture threshold of 140g according to Ono. Of the helmets currently on the market the Schutt Vengeance appears to offer the best protection against linear accelerations (i.e., forces that induce focal head injuries, such as skull fracture), while the Schutt Air XP Pro offers the best protection against angular / rotational accelerations (i.e., forces that cause concussions and subdural hematomas). Overall none of the helmets provided significant protection against concussion.

Unlike the results from the Rowson study above, the 1930’s leatherhead offered greater concussion protection than some of the current helmets on the market. In addition to the standard drop test studies, there have been attempts to compare football helmets on the field as well. One study looked to compare concussion rates among 2,081 high school players during the 2012 and 2013 football season. Athletes wore Riddell, Schutt or Xenith helmets with 206 sustaining sports related concussions (n=209). There was no difference in concussion incidence among any of the helmets. Interestingly, those players who wore custom mouth guards actually had a higher rate of concussion, and not surprisingly the incidence of concussion was higher in athletes who sustained a prior concussion within the past 12 months.

Rowson and Duma performed a retrospective analysis of head impact data (HITS systems) between 2005 and 2010 from 8 collegiate football teams. Concussion rates were compared between players wearing Riddell VSR4 and Riddell Revolution helmets. Of the 64 diagnosed concussions 27 occurred while wearing the VSR4 (incidence 8.37 per 100K hits) and 37 while wearing the Revolution (incidence of 3.86 per 100K hits). However, a lower percentage of players wearing the Revolution helmets sustained concussions despite the Revolution players sustaining significantly more impacts. Overall the Revolution reduced concussion risk by 53.9 percent when compared to the VSR4. The authors felt that the difference was likely due to the Revolution’s ability to modulate energy transfer and thus reduce head acceleration, which in turn results in a decrease in neural strain.

This study received significant criticism by the NFLPA concussion committee, more specifically from NFL player Sean Morey who felt the concussion rates were too low (likely due to under reporting) and were three times less than that of the NFL. They also felt that some of the Ivy League schools in the study were not representative of intensity and speed of Division 1 college football or the NFL. The authors of the original study do a good job of rebutting some of Mr. Morey’s claims. Studies on other types of helmets although somewhat scare have shown similar results.
HOCKEY HELMETS
A recent study out of Canada looked at 10 of the more common hockey helmets using a Kingston Impact Simulator, which uses a pneumatic piston to stimulate rotational forces in the horizontal, coronal and sagittal planes. Acceleration was measured by a digital accelerometer mounted on the head form in various locations and unlike out study above where rotational acceleration was measured directly, the authors used a physics formula to convert linear acceleration to angular acceleration, with an acceleration threshold of 4000 rad/s² and duplicated the impact locations found by Pellman, et al. in their NFL study (see above). The results demonstrated significant variability’s in protection from rotational acceleration and this protection can vary depending on where on the helmet the force is delivered. In fact there were differences among the same helmet brand.25

BICYCLE HELMETS
Finally, drop tests on bicycle helmets when compared to non-helmeted head forms show a significant reduction in peak linear acceleration and calculated Head Injury Criterion (i.e., from 824g to 181g and 9667 to 1250 non-helmeted versus helmeted). This reduction is statistically significant and when taking into account the thresholds discussed above demonstrate the bicycle helmet tested was highly effective in reducing the risk of severe brain injury.27

ADJUNCT THERAPY?
In an effort to improve helmet performance in lowering the risk of concussion certain manufacturers have developed helmet add-ons. We recently evaluated four football helmet add-ons: Guardian Cap, UnEqual Technologies’ Concussion Reduction Technology (CRT), Shockstrips and Helmet Glide. When compared to a stand alone helmet the Guardian Cap, Concussion Reduction Technology and Shockstrips products all reduced linear acceleration by about 11 percent, however their effectiveness in reducing angular accelerations was only two percent and they were completely ineffective in lowering rotational acceleration (unpublished data to be presented at the AAN Meeting in 2015).

Finally it is widely believed that the only way to truly prevent concussion is to completely immobilize the cervical spine. This of course is impractical, as it would place the athlete at risk for spinal cord injury. However, neck collars have been used to decrease head and neck loading and rotational acceleration. The three most common collars are Cowboy, Bullock, and Kerr, and have been tested for their load limiting capabilities using front, top and side helmet impacts. Using angular rate sensors in head and chest, load sensors in the upper and lower cervical region and a head accelerometer researchers found the Kerr collar substantially reduced lower neck movement, with load reduction directly correlating with restriction in head and neck motion.30

Other experts, myself included, have recommended neck-strengthening exercises to their patients. A company out of South Florida has developed a neck strengthening device which it claims can help reduce concussion. Cervifit a small plastic device that uses a set of small, four- and five-pound iron weights stacked at the top. Strapped to the head, the company claims it creates up to 40 pounds of resistance when the wearer performs a series of neck lifts and other exercises. The device is being marketed as a concussion prevention device despite any studies showing that it sufficiently strengthens neck muscles to prevent concussion.

MONITORING PLAYERS AND DATA, IN GAME
Attempts to find an objective on field assessment of head impacts have resulted in the development of the HIT System. As stated above the system uses an array of accelerometers (six total) in the crown of a player’s helmet to measure linear acceleration. The device is unable to measure rotational and angular acceleration and therefore cannot measure the major forces responsible for inducing concussion. The device contains microscopic crystals and functions based on what is called the piezoelectric effect, i.e., the crystal structures are stressed by forces of acceleration resulting in a recorded voltage. The more force that is dealt onto the crystal structures, the more voltage they produce and conversely the amount of force that it took to produce the voltage can be determined by using the recorded output voltage and the sensitivity of the accelerometer.29 The accelerometer must be held close to the skull to avoid measuring the acceleration of the helmet rather than the head. There is no accelerometer on the top of the head (most hits are dealt to the side of the helmet) and therefore if a player leads with his helmet the device will not trigger.

“The best mechanisms to diagnose and prevent concussion include education and awareness, properly trained individuals on the sidelines, rule changes (i.e., not leading with the helmet), teaching proper tackling and hitting techniques, neck strengthening exercises and a comprehensive concussion based neurological history and concussion specific neurological examination.”
The second aspect of the system is the Sideline Response System (SRS), which records the data. If a player suffers a hit with a force of acceleration that exceeds a predetermined threshold (usually >98 g) the team’s medical staff is alerted of a possible concussion, at which time the player is immediately removed from play and undergoes a sideline evaluation for concussion.

There are a number of products currently on the market (with many in development) that use the HITS/SRS technology. The two most widely recognized are the Riddell InSite Impact Response System ($1,000) an integrated system that utilizes the HITS/SRS technology which is embedded into a specifically designed helmet (Riddell Revolution Speed/SpeedFlex) and a software system that alerts the sideline (via a hand held device) to single or multiple impacts that may result in a concussion. The system can also track player hits over the course of a season.

The Reebok Checklight ($150) is a skullcap with an LED indicator hanging down the back of the neck. It is designed to light up if you’ve taken a blow to the head strong enough to possibly cause injury. Green means go, no impacts measured; amber signals a moderate amount of force was detected and red indicates that player has suffered a hit with a force that could potentially cause concussion.

How accurate is the HIT system? Validation studies have been performed (Beckwith 2012 and Rowson/Duma 2011) however a lack of acceptable thresholds makes interpretation difficult. Jadischke and Viano28 have questioned the results based on the size of the helmet used i.e., medium helmet on a large head which could cause increased compression on the springs used to keep the accelerometer in contact with the dummy head, thus resulting in skewed data. They performed testing utilizing medium and large helmets and found significant discrepancies in linear and angular acceleration between the HIT data and laboratory data especially when the facemask was contacted. Overall there was a 15 percent difference in impact acceleration which clinically translates into concussions in concussed players being missed and non-concussed players being excluded between 56 and 89 percent of the time.

CONCLUSION

Helmet manufacturers will continue to attempt to improve helmet design, more add-ons will follow and it appears that more and more amateur sports organizations are turning to HITS technology to help diagnose concussion. The technology has great potential as a research tool, especially when used to study sub-concussive impacts. It will never truly be able to diagnose concussion as it cannot measure rotational acceleration. The biggest drawbacks may be the price, a high false positive rate and the potential for coaches, trainers and physicians to ignore athletes who may have sustained a concussion if the device does not trigger. The best mechanisms to diagnose and prevent concussion include education and awareness, properly trained individuals on the sidelines, rule changes (i.e., not leading with the helmet), teaching proper tackling and hitting techniques, neck strengthening exercises and a comprehensive concussion based neurological history and concussion specific neurological examination.

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