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Impact Attenuation Values and Prevention of Head Injuries on Sports Fields: Do Athletes Deserve Protection the Same As or Better Than in an Automobile Crash?

Reference

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ABSTRACT

In the United States in the period from 2001 to 2005, there were more than 560 000 football- and soccer-related injuries per year among all age groups that resulted in an emergency department (ED) visit, and over 32 000 were traumatic brain injuries (TBIs) (Gilchrist, J., Thomas, K. E., Wald, M., and Langlois, J., "Nonfatal Traumatic Brain Injuries from Sports and Recreation Activities—United States, 2001–2005," *MMWR Weekly*, Vol. 56, No. 29, 2007, pp. 733–737). U.S. Centers for Disease Control and Prevention statistics for 2001 to 2009 for patients 19 years and under indicate that for football- and soccer-related injuries, annual ED visits numbered 487 000, and the number of TBIs was 35 800 (Gilchrist, J., Thomas, K. E., Xu, L., McGuire, L. C., and Coronado, V., "Nonfatal Traumatic Brain Injuries Related to Sports and Recreation Activities among Persons Aged ≤19—United States, 2001-2009," *MMWR*, Vol. 60, No. 39, 2011, pp. 1337–1342). It is suggested that TBI, especially in children, is underreported by as much as 10-fold. A concussion in a child or a high school or college-aged patient can have long-term debilitating

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effects, as such patients recover slower than adults or professional athletes, and a second concussion prior to complete recovery from the first could be life-altering. Studies suggest that the current thresholds in ASTM F1936 for sports fields should get another look from injury-prevention specialists and advocates. It is suggested that for fields being utilized for both helmeted and non-helmeted sports, the test be performed with a hemispherical headform and that both G_{max} and head injury criteria be considered. The playing surface industry was still operating in the 1970s to 1980s with threshold values of G_{max} not exceeding 200 *g* for establishing the limit for fields in use. There are injury data to support a reduction of G_{max} to a maximum of 125 *g*, and consideration should be given to reducing it to 110 *g*.

Keywords
impact attenuation, TBI, head injury, sport fields

A Discussion of the Current Head Injury Prevention Strategies as They Relate to Concussion and Head Injuries on Playing Surfaces

A concussion is a serious head injury that often occurs on sports fields. Annually in the United States between 2001 and 2005, there were 395 369 emergency room visits for all football injuries, with 22 689 concussions, and for soccer injuries there were 169 373 emergency room visits and 9371 concussions [1]. In the single year from July 2000 to June 2001, more than 375 000 nonfatal football injuries were treated in emergency departments (EDs) in the United States [2]. This does not take into consideration that many college, semi-professional, and professional teams have their own medical staffs, and thus their injuries will not appear in the records for national emergency room visits. Additionally, the ED has not been the best suited for treating non-life-threatening injuries for many decades, and treatment of such injuries in other locations makes the number of injuries appear to be decreasing rather than increasing. U.S. Centers for Disease Control and Prevention (CDC) statistics for 2001 to 2009 for persons aged 19 years and under indicate that for football and soccer, the annual number of ED visits was 587 000, and the number of traumatic brain injuries (TBIs) was 35 800 [3]. It has been suggested that up to 3.8×10^6 children and adults sustain a concussion each year [4], rather than the previously suggested 300 000 [5], and this might be an underestimate due to the challenges in identifying concussion, particularly in young children [6–8]. By far, motor vehicle accidents result in the greatest number of head injuries and deaths (61 %) [9]. Consequently, the bulk of the testing programs and studies related to the prevention of all related injuries, and in particular head injuries, have been done by that industry. More recent information from the U.S. CDC indicates that motor vehicles and traffic are now responsible for 17.3 % of TBIs and 31.8 % of deaths due to head injuries, which can provide insight regarding positive outcomes of injury prevention strategies that can be utilized in sport-related TBI [10].

Collisions with sport surfaces account for 10 % of the injuries in American football [11], and they account for 16 % of soccer injuries [12]. Other research shows that of 1003 collegiate football concussions, 22 % were the result of impact of the head with an artificial surface; this number was approximately double that on natural turf [12]. In a study of 25 National Football League (NFL) players having suffered 31 concussions, the incidence of concussions related to head-to-turf contact was roughly 10 % [13]. Thus the impact-attenuating properties of the turf will have a significant effect on the rate and severity of concussions in both soccer and football.

On the sports field, the surface is a contributing factor in the impact of the falling player, whether the impact is to the head or directly to a part of the body with sufficient force to be transferred to the skull and brain. The following pages contain a review of the related literature and research and a thorough discussion of the issues. It is the intent of this paper to present conclusions and recommendations to those responsible for public health, injury prevention, regulations, and standards as to changes that should be made to existing documents for better prevention of severe and life-threatening injuries in such a manner that users will understand the ramifications of their choices and the decisions of others on their behalf.

Traditionally the impact-attenuating properties of playing surfaces have been assessed with the ASTM F355 "A" missile for all natural and synthetic sport surfaces [14], and the hemispherical headform of ASTM F1292 [15] is traditionally used for playgrounds, some additional playing surfaces utilized for sports such as rugby, pole vault landing pads and box collars, and indoor wall/feature padding. The A missile was based on Ford and General Motors test data from the 1960s and 1970s and placement of an accelerometer in a middle linebacker's helmet, which established an impact threshold of 40 ft/lb. As a result the established missile was 20 lb with a flat face of approximately 20 in.^{2}, and it was to be dropped from 2 ft to replicate the 40 ft/lb impact [16]. The 4.5-kg hemispherical headform prescribed by ASTM F1292 is used to simulate the mass of the average adult human head severed at the C3 vertebra, very similar to the mid-adult Hybrid III headform. The Clegg device is a 5-lb flat-faced hammer originally developed to measure the hardness of surfaces such as roads, and according to the device inventor and manufacturer it cannot be used to determine impact attenuation as required for injury prevention. Attempts at developing correlations between the A missile and the Clegg have been a failure, as the material, temperature, moisture, and other factors will change the value non-proportionately. More recently, new impactors have involved the placement of accelerometers inside a football helmet and have been used in conjunction with live subjects or Hybrid III (50) 4.54-kg headforms inserted in sports headgear.

Overview of Head Injury

Statistics indicate that head injuries, and specifically TBIs, are happening at an alarming rate on playgrounds and athletic surfaces. TBIs are complex physiological and neurological events that are underreported to a high degree, mainly because of the lack of outward physical injury that would invoke the traditional ABC's (airway, breathing, and circulation) of any first aid course. The complexity of diagnosis of head injury and the potential for head trauma during play, compounded by the risk of a lack of diagnosis or misdiagnosis of the initial damaging impact and the threat of more serious damage caused by secondary or recurring impacts, make such injuries very difficult for untrained persons to detect; in fact, even trained persons with scientific instruments may have difficulty. In order to better understand the issue, it is important to understand some of the history related to and advances made regarding impact attenuation and its relationship to the protection of humans. This involves a closer look at past analysis methods, from cadaver and primate studies to more current and sophisticated football helmet studies and injury reconstruction analysis. In the end there must be a universally accepted premise that no one wants to unknowingly seriously injure another person. Standard-writing organizations, along with industry and injury prevention organizations, must look to set impact-attenuation thresholds that protect children and athletes from unreasonably serious injury. It is anticipated that review of the current research and the conclusions of future research will result in the conclusion that current thresholds for impact attenuation need to be significantly lowered in order to provide a level of protection equal to or better than that provided by the current National Highway Traffic Safety Administration (NHTSA) standards.

Traumatic Brain Injury

The 2008 consensus statement from the International Symposium on Concussion in Sport defines concussion as "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" [17]. Concussions have five major features.

1. Concussion may be caused by a direct blow to the head, face, neck, or elsewhere on the body with an "impulsive" force transmitted to the head.
2. Concussion typically results in the rapid onset of short-lived impairment of neurologic function that resolves spontaneously.
3. Concussion may result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury.
4. Concussion results in a graded set of clinical symptoms that might or might not involve loss of consciousness. Resolution of the clinical and cognitive symptoms typically follows a sequential course; however, it is important to note that in a small percentage of cases, post-concussive symptoms may be prolonged.
5. No abnormality on standard structural neuroimaging studies is seen in concussion [17].

The biokinetics that induce a concussion consist primarily of acceleration, deceleration, and rotation forces [17]. Direct impact with the head carries a high risk for a concussion, but significant impacts between the body and the impacting surface can also lead to concussion. This is particularly the case in sport- and play-related injuries, as such activities result in impact and rotational forces being transferred to the brain within the cerebral fluid within the skull. Ultimately the concussion occurs when the brain moves about inside the spinal fluid as a result of the force of an impact. The brain can hit the skull from the inside, and that can tear some blood vessels, injure some nerves, and even leave some bruises on the brain [18]. Injuries such as diffuse brain tissue injuries have been demonstrated to not necessarily require linear or skull impacts such as those defined as causes of concussion [19].

The effects of multiple concussions and the cumulative effects of concussions have been studied in organized sports. In such studies, trainers and coaches capture the data and record the events as they occur. High school athletes with three or more prior concussions are more likely to experience on-field positive loss of consciousness, anterograde amnesia, and confusion following a subsequent cerebral concussion [20]. One of the authors of a foregoing study, Dr. Michael Collins, director of the University of Pittsburgh Medical Center's Sports Medicine Concussion Program, states that six to eight high school football players die each year because of "second impact syndrome" [21]. Repeated concussions without full recovery are considered to have led to clinical depression, mental illness, and premature death in former football players and boxers. Another study involving 2488 retired NFL players with an average age of 58 and an average NFL career of 6.7 years showed that 61 % had sustained at least one concussion, and 30 % had suffered more than three. Of these 2488 athletes, 263 (11 %) had been diagnosed with clinical depression [22]. Professional boxers receive repeated blows at approximately 52 *g*, which has been equated to being hit with a 13-lb (5.9-kg) bowling ball traveling at 20 mph (32 kph) [9].

Current Guidance for Sport Field Surfacing Requirements

The fact that concussions occur on sport fields and are serious head injuries with the potential for life-changing consequences for the athlete is irrefutable. Concussion symptoms are ten times more likely to go underreported and be left untreated in instances where there is no external physical manifestation as perceived by the athlete's associates. Familiarity with the athlete's moods, habits, and other behaviors may be critical in forming a baseline that could allow one to determine changes possibly related to a concussion. An ImPACT assessment might be critical in a proactive treatment program. As a result, it is important to investigate the forces that cause a concussion and methods of measurement in the field in order to minimize the frequency and severity of impacts in general and with the surface specifically.

Determination of Impact-Attenuation Values in Standards

A review of the history of various playing surface standards in relation to injury protection, testing procedures, and performance will familiarize the reader with current standards.

One could say that this is where the ASTM standards on surface impact attenuation became tied to the past. Standard writers have been slow to respond to advances in the study of head injuries or changes in thresholds and potential for reduction of injuries. At the same time that Shiffer and his task group were working on playground surfacing, the United States Consumer Product Safety Commission (CPSC) was working with a group in the ASTM F15 Committee on Consumer Products to develop a standard consumer safety performance specification for playground equipment for public use, which was first published as ASTM F1487 in 1993 [23]. In preparation for this work and to reconcile questions of human factor dimensions in the 1981 CPSC Handbook, the CPSC engaged the Comsis Corporation to prepare "Development of Human Factors Criteria for Playground Equipment Safety" under contract #CPSC-C-88-1231 [24]. This report was delivered in March 1990 and approved by the CPSC in May 1990. It included more than 30 pages of analysis of issues related to impact attenuation of surfacing, head injuries, and injury prevention.

The 1990 Comsis report [24] includes an extensive review of the existing literature and investigation of the issue of injuries, and it is very detailed with regard to the impact-attenuating properties of the surface under and around playgrounds in particular. It is likely that the severity of the head injuries being classified as superficial in the 1980s would, in terms of modern-day diagnosis, be significantly understated, and the incidence of TBI would likely be found to be very high. Even with this being said, the incidence of serious head injuries that today would be classed with an Abbreviated Injury Scale (AIS) score of 4 was in the range of 12 %, and that of skull fracture was 6 %. Being in the AIS 4 category, these would be considered beyond the threshold and "life-threatening, with survival probable."

With regard to the impact-attenuation values, the Comsis report acknowledged the selection by the CPSC of a maximum acceleration of 200 *g* because finite modeling, which exists today, was not available, and the thresholds at the time were based on skull fracture. They were able to determine that 80 % of concussions, which at the time were associated with unconsciousness and rupture of blood vessels (subdural hematoma), were associated with linear skull fractures. Today nine of ten concussions occur without loss of consciousness and therefore would not have been taken into consideration in the 1980s. Additionally, they reported that brain damage and concussions did not necessarily require a skull fracture. They also reviewed new measures of both the severity index (SI) and head injury criteria (HIC) and found that an SI value of 1000 corresponded with the median SI value that distinguished between survivors and nonsurvivors in simulated accidents. The SI value required less sophisticated calculation than the HIC and was initially used in playground standards around the world at that time. HIC, which in the end was recommended by the CPSC, always has a lower value than the SI for the same drop data by approximately 20 % because of the nature of the algorithm being applied. As a result, an HIC of 1000 would actually indicate an SI of 1250, and an SI of 1000, accepted in other standards, should equate to an HIC of 800, which would have been more appropriate. The computer program attached to ASTM F1292 for calculating HIC indicates this problem of the need for considerable computing capability, whereas today computer language improvements make it a straightforward calculation.

The testing for impact attenuation for sports fields was based on the ASTM F355 A missile. This missile and the impact-attenuation requirements were developed jointly by the technical representative within the Monsanto Company and the Uniroyal Company under the direction of Dewey Morehouse at Penn State University in State College, PA. ASTM F355 was developed for natural and synthetic turf playing systems and for shock-absorbing cushions for playing systems. In the 1970s the ASTM F08 Committee on Sports Equipment and Facilities created a task group on playing surfacing, which evolved into the F08.52 Subcommittee on Miscellaneous Playing Surfaces. Their first standard, ASTM F355, was published to outline the laboratory and field test methods for playing surfaces. This standard became the dominant industry practice for measuring the impact attenuation of surfaces, and "Procedure A" was the test device and method used for testing sports fields; this procedure eventually became ASTM F1936, in 1998 [25]. The A missile was based on a Northwestern University linebacker in scrimmages. The dynamics of a surface undergoing an impact test are strongly affected by the mass, shape, and material properties of the missile and by the velocity with which it strikes the surface [26]. The Procedure A missile has been shown to have a bias toward thin, soft surfaces, whereas the rounded missile tends to penetrate these surfaces and bottom out before the impact is absorbed, which could also be a result of its lighter weight [26]. During the 1990s there was an evolution in turf manufacture to infill and concept, and the impact-attenuation properties changed from those of an underpad system to those provided by the surface infill.

For football surface testing, the pass/fail of a G_{max} not exceeding 200 g became formalized in ASTM F1936 in 1998, but it was industry practice prior to that, according to a historical account by Breeland [27]. The history suggests that newly manufactured samples of stadium surface systems test below 100 G_{max} (typically with a value of 75 G_{max}) when tested at 21°C to 24°C (70°F to 75°F) and 60 % to 65 % relative humidity. Soccer fields are tested using the same method, but the shock attenuation typically exceeds 200 G_{max} [27]. Suggested thresholds presented by Breeland are displayed in **Table 1**.

With the publication of ASTM F1936 in 1998, there was a need on the part of the subcommittee to write a rationale for the standard acknowledging that "according to historical data, the value of 200 G is considered to be a maximum

TABLE 1 Shock attenuation of football fields [27].

	Desired G_{max}	Typical G_{max} Range
New fields	<100	75 to 125
Old fields	<150	75 to 350
Suggested G_{max}: 225		

threshold to provide an acceptable level of protection to users" and "the maximum impact level of 200 average G_{max} as accepted by the U.S. Consumer Product Safety Commission, was adopted for use here" [28].

Development of Impact-Attenuation Testing and Criteria

It should be noted that the selection of G_{max} equal to 200 *g* is based on subhuman primates, large animals, and cadaver studies. Although these subjects have been used throughout medical history and such research continues today, the early studies using cadavers and subhuman primates in the study of head impact date back to World War II. Many studies investigated the relationship between linear acceleration and damage to the skull or brain. In one such study in the late 1950s, the U.S. Air Force performed studies on anesthetized hogs, and the results indicated that impacts with a duration of 4 to 8 ms and impacts of up to 125 *g* showed reversible injuries, whereas impacts ranging up to 220 *g* and having the same duration resulted in serious to fatal injuries [29]. Similar studies at Wayne State University resulted in the development of the Wayne State Tolerance Curve (WSTC), a roughly logarithmic curve that describes the relationship between the magnitude and duration of the impact acceleration and the onset of skull fractures, in the early 1960 s [26].

The WSTC has formed the basis of mathematical modeling for the development of injury tolerance curves and better understanding of the injury data that are now being produced in work with human surrogates (crash test dummies). The first major advance in the development of mathematical models was the plotting of the WSTC on log paper by Gadd, resulting in an approximately straight-line function for the weighted impulse criterion, which became known as the Gadd Severity Index [30]. This scale took into consideration the entire volume under the impact attenuation curve, and the threshold for life-threatening injury was determined to be an SI not exceeding 1000. In 1972, the NHTSA defined the relationship between the WSTC and the SI as modified by Versace in 1971 as the HIC [30]. Prasad and Mertz compared a collection of skull fracture and brain injury data with their corresponding HIC values and suggested that at an HIC value of 1000 there is a 16 % risk of life-threatening brain injury in the adult population [31,32].

The HIC value of 1000 has been used as the pass/fail in a number of performance standards for the prevention of life-threatening injury [15,33,34] in the measurement of impact-attenuating surfaces in playgrounds, without consideration of the 1000 HIC value being the tolerance threshold for the adult male. The use of the 1000 HIC in these standards had been perpetuated by tradition and only began to be called into question by the ASTM F08.63 subcommittee in 2010. It has also been believed that an HIC of 1000 is the threshold for life-threatening injury, when it is actually 16 % beyond. HIC has been associated with turf systems as a test for non-helmeted sports [35], and for turf in general with a modification of the HIC calculation [26]. The use of HIC in recent turf concussion studies and the acceptance of HIC as a generally universal calculation for the prevention of head injury in automotive studies [36] make this a factor to be investigated for use in sports field turf testing, as a concussion results from an impact to the upper body or head with an effect on the brain. The first use of HIC in sports field surfacing performance was by the International Rugby Board (IRB) in Regulation 22, requiring critical height testing according to EN1177 for laboratory and field [37] using a 4.5-kg hemispherical headform.

For the past 45 years, the sports field industry has been influenced by the companies who designed, manufactured, and installed turf systems with a pad for sale initially to owners of stadiums and sports facilities. In these short pile (0.5 in.) plus mat systems, it can be shown that the cylindrical missile introduces a bias in test results [26], and the systems have evolved to long pile (1.5 in. to 2 in.) stabilizing the impact-attenuating infill materials, for which the hemispherical test missile shows a bias [26]. The bias of either missile to a surface style or type should not spur a change in missile. An additional consideration for usage is that fields initially were in major sporting venues with very few playing hours per week, but they have come to dominate community fields, and where lights are provided they are being used for up to or more than 100 h/week. This usage of almost one traditional year of use in little more than two weeks has changed the maintenance requirements, and particularly the ability of a field to continue to provide impact attenuation. Additionally, over the past 10 to 15 years, the proliferation of technology and the ability of contractors not directly associated with the turf manufacturer to create their own custom orders has allowed installation companies to begin to offer turf systems without the direct integration of the installer with the manufacturer. This changes the manner in which fields are marketed, maintained, and warranted. This has ramifications for the owner and potentially for the impact-absorbing properties of the surface over the long term.

In the present marketplace there are very few large turf manufacturers or suppliers, but there are a multitude of sales and private-label organizations providing systems subject to third-party designer specifications, maintenance demands, and warranties. There is the expectation on the part of the installing organization that maintenance and therefore impact attenuation and warranty compliance will be the responsibility of the owner or operator. In practice the owner/operator maintenance program is short lived, abandoned through lack of training or subcontracting to outside maintenance firms. There is a lack of active firms involved in the maintenance of the installed systems, making this a new growth industry and creating a need for competence in performance to standards. These problems coupled with the increased usage do not bode well for the owners of turf systems, who might have an expectation of a 10- to 15-year functional life including continued impact attenuation.

Field owners are taking actions on their own with testing and maintenance programs to ensure compliance to their own performance standards. Care must be taken to establish a program with regard to maintenance/warranty compliance and injury prevention that will at a minimum follow known consensus standards and devices such as ASTM F1936. An owner using a known standard will have the ability to perform more testing, which will only enhance injury prevention and reduce liability; however, mixing and matching standards and devices could leave the owner or developer of the programs open to liability in the event of injuries or noncompliance with the terms of warranties for the turf system. In terms of artificial turf impact-attenuation testing, there is an active technical subcommittee for this matter at ASTM, and this group has responded to the need to increase injury prevention with the addition of a minimum of four test locations on a field for impact testing, requiring measurement of the depths of the surface system at three points for each test location and expanding the field configurations for sports other than North American football. There is also encouragement to test additional locations on a field for impact attenuation that might come to the owner's or operator's attention as having less than optimal performance as a result of wear, weathering, or other factors. Failure to include this standard or a better practice as a minimum in any field testing and maintenance program will haunt the owner the instant a preventable injury occurs. This is particularly important when lowering of testing criteria or devices is done for convenience or expediency.

Additional turf standards have been developed to improve the quality of manufacturing and installation of turf systems. These include ASTM F1015 [38], ASTM F1551 [39], and ASTM F1936 [25]. A review of the specifics of ASTM F1936 might be instructive for one who wishes to understand how this standard is central to the prevention of injuries in sports under its jurisdiction.

The scope of ASTM F1936 states that it sets the maximum impact-attenuation value for all types of turf playing systems. The standard requires that the average G_{max} at any test point not exceed 200 g, and should this value be exceeded, the turf system is not to be used until the surface complies with the standard. There should be at least ten test points, with eight being specifically located where high traffic and wear are anticipated to take place and two being randomly selected locations, with some guidance as to the location in the document. There are layouts for North American football, soccer, field hockey, field lacrosse (men's and women's), baseball, and unlined fields for multiple applications. This allows the owner or operator to make certain safety statements with regard to the points tested. The more locations that are tested, the better assurance the owner has of compliance. A balance will have to be struck between the number of test locations and time and practicality. The cost of testing should never be considered where the prevention of a brain injury is concerned.

ASTM F1936 does more than measure impact attenuation that is both practical and of benefit, with the required measurement of the depth of the turf system in three locations at each of the impact-attenuation test locations. Depth has a number of critical aspects that require an expanded understanding of turf system design and field construction. Because ASTM F1936 calls for measurement of the depth of the surface system at three points per test location, additional depth tests, without impact testing, can be performed around the field and provide beneficial data. Should the depths at these additional points be within the depths taken at the actual tested points for impact attenuation, performance can be assumed. The only caution is that this requires that the makeup of the infill be consistent.

Two contributors to the impact attenuation of the field system were introduced to the original low-pile/thin-pad systems: the infilling of turf pile with a material capable of being absorptive, or the ability of the material to move in relation to an applied force, and the provision of a field-installed pad under the turf system. These systems have had a dramatic effect on the impact-attenuation properties of field systems and are significantly influenced by variations in depth or thickness. Typically, fields with an underlay and infill will have significantly better shock-absorbing properties.

Loose materials have been used as impact attenuators since sand and gravel were first used in playgrounds; however, these materials are easily disrupted. The synthetic turf industry effectively provided a geotechnical solution with the provision of a high-pile turf to stabilize the loose fill and keep it retained at the intended location. Originally these were stabilized sand playing fields, and the marketing aspect of the industry flipped the concept on its head by rebranding the product as artificial turf with infill. This infill material has evolved from the original 100 % sand to mixtures of sand, rubber, and other materials in various percentages to provide proprietary properties for the installed field. There are also fields that have gone to 100 % ground rubber infill. Obviously a single material will be homogeneous in size and specific weight, whereas different materials will have differing sizes and specific weights, which can contribute to stratification of the material. If the material is intended to be a homogeneous mix and it separates, this will change the impact-attenuation characteristics of the system. Where there is a mixture of infill materials, they can be distributed individually across the installed turf and then mixed and pushed into the system using a mechanical brushing technique. This can lead to portions of the system being out of proportion with others and therefore can affect the impact-attenuation properties.

The downside of loose infill material is that it is loose and therefore subject to movement with active play, wind, rain, and other activities that might take place on the field. Even changes of 2 to 3 mm in depth can change the impact-attenuation values for a location.

Once the infill is set and maintained in the field, it is possible to perform impact-attenuation tests according to ASTM F1936, including the measurement of the infill depth to the G_{max} value set by the owner or operator and a G_{max} value not to exceed 200 g. For all of the test locations that provide a G_{max} below the allowable threshold, it is possible to determine the average depth for each location. Additional depths at 50 to 60 additional locations can then be taken, and provided the depths of the infill system are equal to or greater than any of the depths that have a compliant G_{max}, it can be assumed that the G_{max} at these additional locations also is compliant. Noncompliant depths or G_{max} values for any location require that that location of the field be brought into compliance before use.

Another method of providing impact attenuation for synthetic turf is to install a layer of cushioning material under the turf using one of three methods, each of which has attenuation properties determined by the thickness or depth of the system. The first type of system broadly consists of a manufactured synthetic material that provides a high degree of assurance of performance, as the density, thickness, etc. are determined in a factory. Second, there is the bonding of rubber crumb or rubber crumb and aggregate with a polyurethane binder in a predetermined thickness. Where an aggregate is combined with the rubber crumb, it is possible to have inconsistencies due to differences in the specific weights of the materials, but this can be overcome with a high degree of site supervision. The third system involves the bonding of recycled industrial foam chips through the application of heat and pressure. Although the thickness can be controlled in the factory setting, inconsistencies can come from the comingling of differing sizes and densities of foam chips and result in differing impact-attenuation properties. Weighing the product as it is received on site or at the factory prior to shipping and performing other tests for consistency will ensure the success of the installation. Underlayments typically do not deteriorate with time or use, but the depth should be tested and confirmed after installation and in high-traffic areas periodically during the life of the field.

Both loose infill materials and underlayment systems present challenges regarding the determination of depth. The loose fill, which typically does not exceed 40 mm (1.57 in.), can be easily disrupted, and for this reason a three-prong tester capable of penetrating the infill to its full depth is recommended. Additionally, there is a need for the housing to have a surface diameter exceeding 70 mm (2.75 in.) to ensure that the device does not penetrate the system and only the three measuring rods penetrate the system, thereby ensuring accuracy. For infill depth measurement, the prongs can be blunt so as not to penetrate to the backing. For measurement of the depth of the underlay, primarily polyurethane-bound systems, and the entire synthetic turf system, the penetrating rods will have to be sharpened to allow penetration of the turf backing and the underlayment and any geotextile that might be in the system above either a granular or an asphalt/concrete base.

Recording all depths and comparing them to depths of portions of the system that have been tested to ASTM F1936 will ensure that the entire turf system is or can be extrapolated to be within the G_{max} tolerance set by the owner or operator.

Defining the Measurement of the Life-Threatening

The development of the impact-attenuation criteria used to measure impacts on sport field surfaces has been based almost exclusively on the crash test data produced in the automotive industry, with a minor confirming reliance on some military testing. There is significant evidence that a direct impact with the head or an impact to the body with sufficient energy to transmit the force of the impact to the head, combined with sufficient linear or rotational acceleration within a duration interval of milliseconds, will result in a severe head injury. Historically this was determined with animal and cadaver studies, with the results being the WSTC, the Gadd SI, and the HIC. This has remained the commonly accepted threshold since the 1970s and 1980s for reducing the risk of a life-threatening or permanently life-altering head injury. This HIC value of 1000 was at the time based on a large adult male. There were no other data or scaled values available. Additionally, the HIC calculation was not constrained as to the duration of the interval of the impact. Even so, this calculation was then translated to ASTM F1292 [15,40]. Since 1993 there have been significant advances in the evaluation of head injury and the impact threshold values related to an acceptable injury severity.

In October 1996, the NHTSA recommended that the calculation of HIC be constrained to 36 ms (HIC_{36}), as longer intervals had not shown low probabilities of injury in voluntary human subject tests, and the HIC of 1000 for the unconstrained HIC would be roughly equal to HIC_{36} 1000. Additionally, the test data for head impacts studied by Mertz et al. in 1996 [31], Hodgson et al. in 1971 and 1973 [41,42], and Got et al. in 1978 [43] were all found to involve short-duration impacts of less than 12 ms [36]. As a result, both HIC_{15} and HIC_{36} could be applied to the data. It was determined by the industry group making recommendations to the NHTSA that the limit values related more to the HIC_{15} and should be applied with a maximum HIC value for a mid-sized male of <700 [36]. Through scaling it was determined that the HIC_{15} values for various dummy sizes would be as in **Table 2** [44]. The values in **Table 2** were adopted by the NHTSA as of the final rule making in March 2000 [45].

To provide a measure of understanding for **Table 2**, it is instructive to review the AIS and HIC_{15} thresholds. The AIS was first developed in 1971 to aid vehicle crash investigators in quantifying injury severity and assigning a numeric value,

TABLE 2 HIC_{15} limits for crash dummies of various types.

Dummy Type	Large Adult Male	Mid-sized Male	Small Female	6-year-old Child	3-year-old Child	1-year-old Child
HIC_{15} limit	700	700	700	700	570	390

TABLE 3 Abbreviated Injury Scale (AIS).

Injury Severity	Abbreviated Injury Score
Minor injury	1
Moderate injury	2
Severe, but not life-threatening	3
Potentially life-threatening, but survival likely	4
Critical with uncertain survival	5
Unsurvivable injury (maximum possible)	6
Severity unknown	9

and these values are applied to five body regions, including the head. AIS injury scores run from 1 to 6 as outlined in **Table 3** [46].

During the 1990s, automotive researchers made significant advances in the understanding of injury assessment reference values (IARVs), which were originally developed by Mertz in 1978 and revised in 1993 for response measurement of the Hybrid III small female and large adult male test dummies [47]. Other IARVs were developed for Hybrid III child test dummies. Prasad and Mertz have published injury risk curves for skull fracture and for brain injuries with AIS $\geq$ 4 due to forehead impacts based on the HIC_{15} criterion and for skull fracture based on peak g center-of-gravity acceleration [47]. The result is the HIC_{15} value of 700, which is a conservative estimate of the 5 % risk level of AIS $\geq$ 4 % [47], the current automotive standard in the United States and Canada.

Present sport field surface performance is also partially based on a G_{max} of 200 g, which is based on the U.S. CSPC recommendation for eliminating life-threatening head injuries if the surface could be maintained below this threshold value. It is important to review the risk assessment associated with this value of G_{max}. Studies by Mertz et al. estimated a 5 % risk of skull fractures for a peak acceleration of approximately 180 g and a 40 % risk of a skull fracture for a peak acceleration of 250 g [48,49]. A study by Chan et al. determined that there is a 15 % risk of skull fracture at 124 g, with a 95 % confidence level [50], and Haddadin et al. found a 5 % risk of an AIS $\geq$ 3 at 72 g and a risk of 20 % of an AIS $\geq$ 3 at 88 g [51]. Another factor that might be considered in evaluating the use of 200 g as the threshold limit is that for ASTM F1292, the data have indicated that on average a G_{max} score of 150 g is equivalent to an HIC score of 1000 [52]. This could well be a factor in the final selection of G_{max} for ASTM F1292, and it should be a consideration for ASTM F1936.

Clearly concussions and AIS thresholds of >4 are not the same. It must be determined whether the goal is the prevention of an AIS > 4 or a TBI before thresholds for both G_{max} and HIC_{15} can be established in a standard for playing systems. Concussion studies have mostly been related to data collected from teenagers, college athletes, and reconstructions of concussions sustained by NFL players.

Children pose a unique challenge, because their brains are still developing and are more susceptible to the effects of concussion [17], and because children and high school athletes recover less rapidly than NFL players [53].

There have been two major studies: the NFL study, using a small sample of injured players and specific concussion incidents, and the head impact telemetry system (HITS) study, involving a large number of athletes and thousands of head impacts. Although their conclusions regarding concussions in football are somewhat different, they both consider the incidence of the concussion to be well below the 200 g G_{max} thresholds for turf systems in ASTM standards. Interestingly, both of these studies have consistently included the HIC values and rotational accelerations as very important for understanding the incidence of concussion [54]. This might be a surprise to some involved with athletic turf, either natural or synthetic, as turf is only tested to G_{max} with either a Clegg hammer or the F355-A device [26]. These devices readily record G_{max}, due to the flat shape of the impacting surface, but a modified HIC has been calculated [26]. This has been used to remove the F355-A device bias in favor of thin, soft surfaces, and when the data are adjusted to provide an HIC, these thin systems demonstrate a significantly greater injury risk than thicker systems with infill or padding underlayment (or both) [26].

The NFL study, as it has come to be known, reconstructed 31 NFL collisions, 25 of which involved concussions [55]. These impacts were modeled and impact data were generated at the laboratories of Biokinetics and Associates in Ottawa, ON, Canada, using helmeted Hybrid III test devices, with concussions occurring at $98\,g \pm 28\,g$ and an HIC of 250 [55]. These results were tested as the object of a study by Zhang et al. [56] in which they used a finite element modeling technique and the Wayne State Brain Injury Model to determine G_{max}, HIC_{15}, and rotational acceleration. Their results showed that for the injured athlete, the mean acceleration was $103\,g \pm 30\,g$, the HIC_{15} was 441 ± 224, and the mean rotational acceleration was $7354 \pm 2897\ \text{rad/s}^2$ [56]. A criticism of these values is that they have subsequently become known as the injury thresholds for concussion, rather than exclusively descriptive of the values specifically related to known concussions. This may well be a valid argument, but the evidence demonstrates that concussions are taking place at these values in elite athletes with exceptional protective equipment, training, and conditioning. This would not likely be the case for the high school or college athlete or a child in a playground.

Another perspective on the risk of concussion is the analysis of injury and impact data collected through the deployment of HITS data-collection devices in the football helmets of a large number of athletes. These studies make it possible to collect thousands of impacts and provide data for G_{max}, HIC_{15}, and rotational acceleration for each impact. At some point there is the inevitable occurrence of a concussion, and the impact data prior to the concussion are available for statistical analysis. Through the comparison of impact values for those sustaining concussion and those not, it has been possible to determine that there is a 10 % risk of concussion for a G_{max} of 165 and an HIC_{15} of 400 [57]. This could lead to the conclusion that for some athletes other factors allow them to sustain higher values of peak acceleration without sustaining a concussion; however, in a study of 1712 impacts [57] in which no concussions were sustained, there were only 3 impacts greater than 100 *g*, and only 1 of these was over 120 *g*. Other than these three impacts, the study would tend to lend credibility to NFL values for thresholds below which no concussion is anticipated. This same study shows a high correlation between increasing peak acceleration [57] and increases in angular acceleration, indicating that if rotational acceleration is a factor in concussions, the increasing *g* value could be a predictor of the angular acceleration.

These studies introduce an additional criterion to the traditional linear acceleration for G_{max} and impact duration of the HIC: the rotational acceleration. The inclusion of rotational acceleration acknowledges that most impacts, particularly between athletes, will be from a side or glancing contact, and there will be an impact that is not strictly coup/countercoup, which will allow the brain to move rotationally within the skull and potentially cause shearing of the neuron axons, damaging the protective myelin coating and disrupting communication between cells [58].

The HITS instrumented helmets have increased the amount of data available to coaches, trainers, and team physicians in the monitoring of potential risk of head injury to their athletes. Data collected over the four-year period from spring 2005 to fall 2008 resulted in 71 390 impacts, with a total of 55 concussions caused at $G_{max} = 107 \pm 31$, $HIC_{15} = 272 \pm 213$, and $7079\ rad/s^2 \pm 3408\ rad/s^2$ [59]. In a presentation at the Federal Interagency Conference on TBI, Beckwith presented additional data for the six years from 2005 to 2010 in which there were 90 concussions occurring at a peak *g* of 117 ± 33 and $7266\ rad/s^2 \pm 3400\ rad/s^2$ [60]. The HITS helmets indicate that there are impacts greater than the mean *g* values for those sustaining concussions. These results must give all professionals, particularly those in states where they have a legal responsibility to prevent concussions in their athletes, an exceptional opportunity to meet their responsibilities.

The data, whether from the NFL study or the HITS results, show that a threshold exists between 70 *g* and 150 *g* where concussions are occurring, and the median is likely to fall in the range of 105 *g* to 110 *g*. These values are significantly lower than the threshold for the playground surface of 200 *g* as required in ASTM F1292.

The HITS system has been deployed for a number of years and has been successful in counting the number of impacts that a user receives over the course of wearing the helmet, but the system should not be taken as a definitive measure or device. TBI is very complex and sometimes elusive in terms of determination of the mechanism, and care must be taken to consider all testing measures being utilized as additional tools in the box, but so far nothing can be considered as an absolute. This is particularly the case where rotation is measure external to the skull and directly translated to the brain, brain stem, or neck, as many other factors come into play.

On the basis of the data, this means that the G_{max} of a playing surface system when tested should be less than 105 *g* to 110 *g*, and from the automotive requirements the HIC_{15} should be less than 700 for all ages. These values would potentially prevent both concussions and head injuries with AIS > 4.

Implications for Non-Helmeted Sport

Given the introduction of the HIC, modified as it might be, by Shorten and Himmelsbach in 2003 [26] and the fact that there are more athletes playing on natural and synthetic turf without helmets than with helmets, the practice of testing a synthetic turf with a missile based on placing an accelerometer in a middle linebacker's helmet to establish an impact of 40 ft/lb needs to be examined. An option is to test surfacing using a hemispherical missile designed to simulate the mass of the average adult human head severed at the C3 vertebra. This can be suspended to provide a theoretical drop height equal to the velocity of the falling athlete. Changing to the hemispherical, although not biofidelic, missile will allow the collection of both G_{max} and HIC data. This is precisely what the IRB does by using the EN1177 4.5-kg hemispherical headform from 1.5 ms and setting the threshold at 1000 HIC.

Impact Velocity and Free-Fall Height

In the NFL study of concussions sustained by 25 players, the reproduction of the events indicated velocities of 5.5 to 117 m/s, and the average impact velocity was 9.3 ± 1.9 m/s [13], or the equivalent of a 4.4-m (14.4-ft) free-fall drop. For the three head-to-turf concussions the velocities were 6.0 to 8.3 m/s, and the average velocity at impact for the three concussions sustained as head to surface without prior player impact was 7.5 m/s [13], equivalent to a 2.87-m (9.42-ft) free-fall drop. The average G_{max} for the 25 helmeted football players was 98 *g*, and for the head-to-turf players it was 123 *g* with an HIC of 640. The impact velocities from the study raise the possibility that the current testing with ASTM F355, Procedure A at 2 ft might not generate an adequate velocity. Increasing the drop height for this procedure would make it difficult to ensure a vertical drop, and the mass of the device would be problematic for portability.

Just as the velocity is important, determining the appropriate velocity and being able to perform testing are also important. The NFL study provides one set of velocities, but further information might be required in order to determine whether these are appropriate for fields intended to be used by college, high school, and younger players. If the required height for testing is determined to be 5 ft to 9 ft, then the ability to raise the missile to these heights and keep the missile portable has to be considered.

Implications for Sport Field Owners, Operators, Manufacturers, and Installers

Currently there are a number of laws and mandates in Canada and the United States that require the removal of an athlete following concussion and refusal to allow that athlete's return to play prior to competent medical clearance. Loss of an athlete in any program could affect the outcome of a season, athletes' future professional careers, the current careers of the coaching staff, and the financial viability of the athletic program.

It will be the motivation to prevent injuries and preserve a program that will drive owners to demand better impact-attenuation values, maintenance procedures, and warranties that give them the performance that meets their requirements. The performance requirements will be not only for the new field, but also for the anticipated life of the field.

Owners will also be more involved in maintenance and meeting performance criteria in order to prevent injuries to their players. The dissemination of information and shortened careers will put owners on notice that they may well be responsible for the long-term costs and losses that players and their families sustain. As a result, owners will be seeking testing and maintenance performance that meets the current consensus standards at a minimum, as well as any better practice their risk managers can recommend. It is difficult to say whether the cost of an injured child with a shortened career or a professional athlete being paid out on a contract would be the greater cost to the owner.

For the manufacturer, there will be significant changes in products and marketing strategies to meet the required demand. There is a perception that improved impact attenuation can only be achieved through the "softening" of the field, which would detrimentally affect firmness as it relates to good footing and sport-specific performance for athletes. The very legitimate concern is an increase in lower extremity injuries. A means of balancing the two performance issues would be the inclusion of an underlayment turf system and infill designed to provide all of the desired properties. This field design will likely have financial consequences, and the owners and players will have to take this into consideration when a new field is being designed or purchased.

New field designs offer opportunities for manufacturers and installers of the components of the field, as well as opportunities for ongoing maintenance and inspections.

It is important to review the financial effects and availability of products related to the acceptance of the recommended improvements in impact attenuation of all sport playing surfaces. Currently synthetic turf systems exist that, when installed and maintained to their appropriate depth, can meet the recommendations with very little additional cost. It will be the turf owner not currently meeting the performance criteria or performing the required maintenance who will incur financial hardship; however, it is not the concern of the person working to prevent injuries if an owner does not do the basics that he or she is responsible for. Professional and skilled maintenance service contractors have begun to provide maintenance and testing services, and it is likely that these groups of contractors will grow and become more sophisticated in their offerings in the future.

Implications for Standard-Writing Organizations

Standard organizations such as ASTM provide the facility, mechanism, and procedures to write specifications, test methods, practices guides, etc., with a structure of consensus building. The consensus is built within a matrix of producers, users, and general interest, using current knowledge and best practices to advance standards. At the present time the F08.65 subcommittee is investigating and balloting both the reduction of G_{max} and other factors related to impact attenuation such as annual/seasonal field testing requirements. Given the mountain of evidence regarding necessary improvements for impact attenuation in the field, it would behoove this group to make the changes as quickly and expeditiously as possible.

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