Sports surfaces and the risk of traumatic brain injury

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Introduction

Sports provide many opportunities for an athlete's head to experience an impact or other violent acceleration. Player to player contact, a collision with a goal post or other structure or striking the surface during a fall can all result in brain trauma. Sports are a common venue for concussion, more formally described as Mild Traumatic Brain Injury or MTBI. Indeed, the US Centers for Disease Control and Prevention considers the incidence of sports-related MTBI to have reached epidemic proportions (CDC, 1977). Also, in many sporting contexts, the threat of more severe, life-threatening head trauma is always present.

While severe head injuries are relatively rare, they have the potential to change lives in a dramatically negative way and carry a greater risk of fatality than more common injuries. Consequently, they have been a focus of attention in the sports medicine community for many years. Concern about more minor head injuries has also increased in recent years, with the realization that MTBIs can have cumulative, long-lasting effects on cognitive function and can also expose an athlete to a period of greater risk of severe injury or death from a second or subsequent episode.

The potential for head injury has an influence on the development and marketing of sports surfaces, too. In several cases, the standard test methods used to evaluate and specify the shock attenuation of sports surfaces, crash mats and wall padding are based on the assumption that the there is a risk of head injury and that an appropriately cushioned surface can reduce that risk. For example, a commonly used specification for the shock attenuation of North American football fields (ASTM F1936) is hypothetically linked to the non-fatal

acceleration tolerance of the head. Frequently, F1936 is the only performance-related specification included in a field purchase contract, suggesting that head injury risk is an important consideration in the purchasing decision.

This paper briefly summarizes some of the medical and research literature related to traumatic brain injuries in the context of sports. We also attempt to determine the extent to which sports surfaces represent a risk factor by reevaluating the relationship between the outcomes of common surface impact test methods and head injury risk.

Mechanisms of brain trauma

The extensive medical and biomechanical literature relating to brain trauma in sports has been reviewed recently by Bailes and Cantu (2001) and Wojtys et al, (1999). The fundamental cause of most brain injuries is strain (compression or stretching) of the brain tissue and the blood vessels it contains. Historically, head injuries have been classified in various ways, based on their severity and on the mechanical factors involved in their aetiology. In general, brain injuries can be considered as either "focal" or "diffuse". Focal injuries are typically confined to a local region of the brain and are usually the result of a direct blow to the head. Even if it does not fracture the skull, an event of this type produces a shock wave that alternately compresses and stretches brain tissue, causing local tearing of brain tissue and blood vessels. The subsequent hemorrhaging and haematoma can be fatal.

While a direct blow to a stationary head will normally produce an injury in its immediate vicinity, a focal injury does not necessarily occur at the point of impact. If the head is moving when it experiences a collision, the brain moves around inside the cranium, where it floats in cerebrospinal fluid. Commonly, the brain is traumatized by impact with the skull at a point opposite the point of impact (a "contrecoup" injury). Motion of the brain inside the skull can also lead to cavitation, the formation of a vacuum that can disrupt brain tissue and small blood vessels.

The brain trauma associated with a diffuse injury is often less severe but usually more widespread than with a focal injury. A direct impact can cause a diffuse brain injury but it is not required. A collision in which the head is not directly involved, a hard tackle or vigorous shaking for example, can cause the head to rotate violently. The brain accelerates inside the skull generating injurious strain levels in the process. (The Latin verb meaning "to shake violently" is "concussus", from which the English word "concussion" is derived.) Mild diffuse injuries such as MTBI are characterized by short term cognitive dysfunction and possibly loss of consciousness. More severe diffuse injuries can result in deep, permanent coma and have a mortality rate in excess of 50%.

The relative importance of linear, translational motion and rotational motion of the head in brain trauma mechanisms has been the subject of some debate. It is possible that the distinction between linear and rotational motion is arbitrary, since real events involve some degree of both. A translational acceleration of the brain is more likely to occur when there is a direct impact. A rapid rotational acceleration is more likely to result from an indirect blow and produce a more diffuse injury. High rotational accelerations of the head also cause tearing of the nerve cells in the region of the cerebrospinal junction. An impact between the head and a sports surface can be expected to result in accelerations that are primarily linear, but rotational accelerations are also possible, depending on the geometry of the head, neck and torso at the instant of impact, and the friction of the surface.

The consequences of brain trauma sometimes emerge over time. In the hours and days following the initial traumatic event, physiological changes occur that can have far reaching consequences. When brain cells are torn, calcium and potassium ions escape into the surrounding interstitial fluid (Katayama et al, 1990). Since nerve impulses are transmitted by the flow of these ions across cell membranes, the released ions can disrupt neural function. What follows is a "metabolic cascade" of events as healthy cells try to compensate for the

uncontrolled flow of ions, demanding more energy and consuming more glucose in the process. This metabolic distress leaves the brain vulnerable for some time after the initial injury, increasing the probability of a further injury. Guskiewcz et al (2000), for example, found that football players who had experienced a concussion were three times more likely to experience a second concussion in the same season.

Surfaces as a risk factor

The extent to which sports surfaces are a factor in brain injury is unclear. The incidence of injuries of all kinds has been well documented for most major sports and recreational activities, but these studies rarely distinguish impacts with the surface from other impacts, nor do they document the surface type or condition involved in a head injury. However, it is reasonable to believe that a collision between the head and a surface has the same injury potential as a direct impact with any other object and the limited information available supports this assumption.

Falls to the surface account for 21% of the deaths in playground equipment-related accidents and most of these (~75%) involve catastrophic head injury (Tinsworth et al, 2001). "Unsuitable surfacing" has been found to account for between 79% and 100% of severe head injuries (Mack et al, 2000).

It can also be shown that different surfaces present different risks of head injury. For example, the risk of serious head injury following a fall is 1.7 times greater on a grass surface than it is on sand (Laforest et al, 2000). Clarke et al (1978) found no difference in the incidence of MTBI between natural and artificial turf while Naunheim et al (2002) suggest that risk is higher on artificial turf. Neither study presents convincing evidence, however. More persuasive is the study of Guskeiwicz et al (2000) who tracked injury rates among 17549 high school and collegiate football players. They documented 1003 cases of MTBI, of which 10% were due to impact between the head and

the playing surface. The rate of surface-related head injury per 1000 athlete-exposures on artificial turf was approximately double that on natural turf. More significantly, 22% of the concussive impacts on artificial turf resulted in Grade II injuries involving loss of consciousness, compared with 9% of the impacts on natural turf. This finding equates to a five times greater risk of the more severe, Grade II MTBI on artificial turf. Since both "natural" and "artificial" turf encompass a wide range of surface properties the particular characteristics that caused the difference in head injury incidence remains unknown.

Assessing head injury risk

The published research shows that impact is strongly implicated in the etiology of traumatic head injury, that sports surfaces present an opportunity for impacts to occur and that different kinds of surfaces present different relative risks of injury. Therefore, it is important to assess how different surface designs and material properties can influence head injury risk.

Epidemiological studies that track sports injuries and document the surfaces on which they occur would be very helpful in this regard, but few exist. If they did, they would tell us about existing, installed surfaces but would not provide a means of evaluating new or prototype surfaces. Laboratory studies with human subjects are also of limited value in this context because the researcher has an ethical responsibility not to expose subjects to the possibility of an injury. Under these circumstances, it is a normal for scientists to use a surrogate, instead of human subjects. Human surrogates commonly used in head impact research include cadavers, anesthetized animals, physical models (e.g. headforms or crash dummies), mathematical models and computer simulations.

Impact Tests as Human Surrogates

An impact test is an example of a physical model, and one that is commonly used to evaluate the shock attenuation performance of both sports surfaces and the protective

equipment used by athletes. An impact may be loosely defined as a brief period of intense acceleration, such as may be caused by a collision. A test of surface shock attenuation simulates an impact by dropping an instrumented weight onto the surface and measuring the resulting acceleration. The acceleration is usually expressed in g's, where one g is equivalent to the acceleration due to gravity. One way to quantify the magnitude of an impact is to measure the peak acceleration it produces. This peak acceleration is commonly referred to as the g_{max} score (Figure 1A).

In order for an impact test to be useful in assessing the potential risk of head injury, three requirements must be met:

1. The tolerance of the brain to impact loads must be documented so that the relationship between impact dynamics and injury risk can be quantified.
2. The impact test must simulate the potentially injurious events that athletes might be exposed to during play. It may be necessary to devise different tests for different sports if they athletes are likely to experience different collision dynamics.
3. There must exist a means of comparing the outcomes of the impact test with impact tolerance data in a way that produces meaningful information about surface performance.

These requirements will be considered in more detail in the following sections.

Impact tolerance of the brain

Early experiments on the ability of the human brain to withstand impact were performed at Wayne State University using human cadavers and animal models (Gurdjian et al, 1945, Gurdjian et al, 1955). This pioneering work eventually led to the publication of the "Wayne State Tolerance Curve" (Lissner et al, 1960; Patrick et al, 1963), a roughly logarithmic curve that describes the relationship between the magnitude and duration of impact acceleration and the onset of skull fractures. The relationship is nonlinear – the head can tolerate

high accelerations for very brief periods but a longer exposure to a lower acceleration level may be damaging. For a given degree of injury the logarithmic slope of the exposure time / acceleration graph is approximately –2.5. Gadd (1966) both discovered and exploited this relationship, proposing the Severity Index (SI) as a measure of the injury potential of an impact. SI (Eqn 1) is the integral of the acceleration time curve, weighted by the 2.5 factor observed in the Wayne State Tolerance Curve. SI is calculated as:

$$SI = \int_{0}^{T} a^{2.5} \, dt \qquad \text{Eqn 1.}$$

where a(t) is the acceleration-time pulse of the impact and T is its duration. Equation 1 can be interpreted as "the area under the acceleration time pulse, after the acceleration values have been exponentiated to the power 2.5" (Fig 1B). An SI score of 1000 approximates the limit of human tolerance. Impacts with a higher score have a greater than zero probability of causing a life-threatening brain trauma.

HIC: The Head Injury Criterion

The purpose of the Gadd's Severity Index SI was to express the shock of an impact in a way that quantifies the risk of head injury. In practice, SI scores are reasonable predictors of the injury potential of impacts that produce focal brain injuries. For impacts of lower intensity but longer duration (i.e those more likely to produce diffuse brain injury), the SI calculation produces unreasonably high values that predict more severe injuries than those actually observed in cadaver experiments. The Head Injury Criterion (HIC) is an alternative measure of impact severity that is not subject to these errors. As a measure of head injury risk, HIC (Eqn 2) is similar to SI in principle but requires that portions of the acceleration-time pulse be analyzed to determine the starting and ending points that yield the highest score. The HIC score is given by:

$$HIC = \max\left((t_1 - t_0)\left[\frac{1}{(t_1 - t_0)} \int_{t=t_0}^{t_1} a_t \, dt \right]^{2.5} \right) \qquad \text{Eqn 2.}$$

where t_0 and t_1 are the beginning and ending times of the portion of the acceleration-time pulse being examined. Equation 2 can be loosely interpreted as "Find the portion of the acceleration–time pulse that has the highest average SI score and use that as the Head Injury Criterion." Exponentiation of the acceleration-time pulse to the 2.5th power (Fig 2B) weights the accelerations according to head injury risk using Gadd's method; de-emphasizing lower acceleration levels and emphasizing higher ones. The integral (Fig 2C) accounts for the duration of the acceleration and an iterative search finds the time interval $(t_0..t_1)$ that maximises the HIC score.

A HIC score of 1000 represents the "safe" limit of human tolerance, above which the risk of a fatal head injury is non-zero. The importance and validity of HIC is frequently debated but the criterion remains extensively used. For example, in the USA, Europe and elsewhere, government mandated performance requirements for automotive seatbelts, airbags and other safety devices are specified in terms of a HIC score. It is similarly applied in the aviation industry and elsewhere. In the sports surfacing world, HIC scores are the primary determinant of playground surfacing shock attenuation performance. Other specifications of surfacing shock attenuation use a 200 g_{max} limiting performance criterion, on the basis that it approximates the HIC limit but is easier to determine.
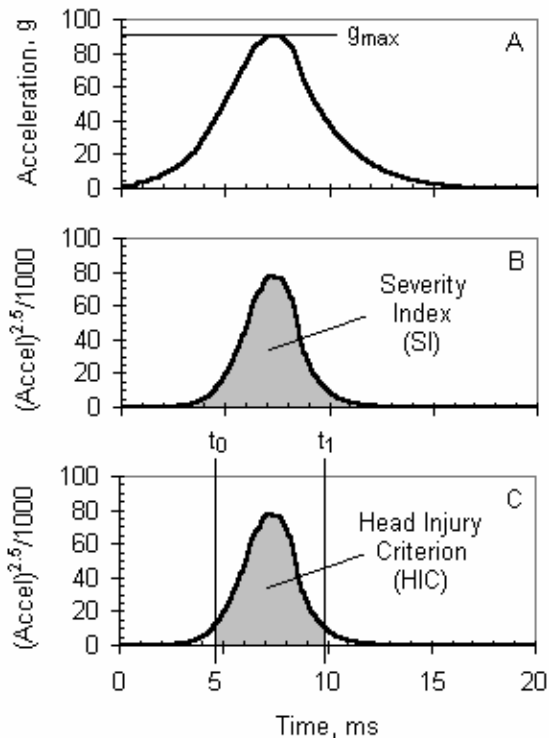
Fig 1. Example SI and HIC calculations.
       (A)   Acceleration-time pulse from an impact between a surrogate head and an artificial turf surface, showing the peak value or g_{max} score.
       (B)   The same pulse with acceleration values exponentiated to power 2.5. The SI score is the area under the curve
       (C)   As (B) but showing the time limits, t_0 and t_1, that maximize the HIC score.

HIC scores as predictors of injury severity
Empirically determined relationships between HIC scores and

the probability of head injury (NHTSA, 1997; Prasad and Mertz, 1985) are widely used in the automotive industry and elsewhere as a way of estimating injury risk. Figure 2 shows examples of "Expanded Prasad-Mertz Curves". Each curve estimates the probability that an impact with a given HIC score will result in a specified level of head trauma.
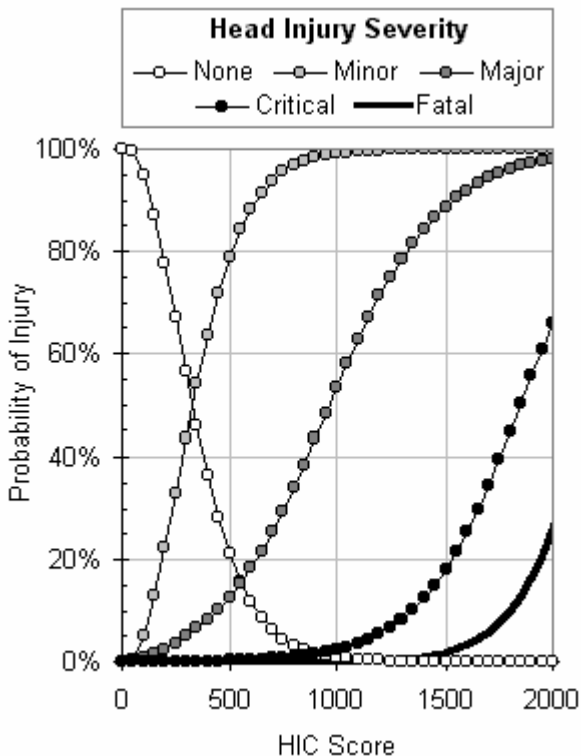

Fig 2. Expanded Prasad-Mertz curves showing the relationship between the HIC score of a head impact and the probability of an injury

For example, consider the case of an athlete experiencing an impact with a HIC score of 500. The curve for a "minor" injury

(i.e. a skull trauma without loss of consciousness) has a value of 79% at a HIC score of 500, indicating that there is a 79% probability that the athlete will incur a minor concussion. At the same HIC value, the risk of a "major" injury (skull fracture, extended period of unconsciousness) is 13%. The risk of a 500 HIC producing a critical or fatal head injury is very low, but the probability of experiencing this head impact and not being injured at all is only 21%.

Surface shock attenuation tests

The ultimate purpose of testing the shock attenuation properties of a sports surface is to estimate the probability that an impact on the surface will cause an injury. In many cases, an absolute measure of risk is not possible and relative measures, i.e. comparisons of the performance of different surfaces, are commonly used.

In principle an impact test is uncomplicated. A "missile" (e.g. a metal sphere) is dropped onto the surface, the impact is recorded with an accelerometer embedded in the missile and the recorded acceleration signal is evaluated. The evaluation might include the calculation of g_{max}, SI and HIC scores, for example.

Example Impact Tests

Worldwide, there are several methods that are commonly used to test the shock attenuation of sports surfaces.

The "Clegg Hammer" is a 2.25 kg cylindrical missile with a 5 cm face diameter that is dropped from a height of 0.46m. The test was originally developed for testing the compaction of road surface, but is specified in ASTM Standard F1702 as a test of the shock attenuation of natural turf. The test method is used for relative assessments of shock attenuation properties and is not used to specify performance requirements.

ASTM F1936 specifies a different cylindrical missile for shock attenuation tests of North American football fields. This missile,

the "F355-A" device, has a face diameter of 12.8 cm, a mass of 9.1 kg and is dropped from a height of 0.61 m. Other tests employ missiles with shapes that more closely resemble that of the head. Tests of playground surfaces (ASTM F1292, EN1177) use either a rigid headform or a hemispherical missile dropped from various heights. Table 1 compares some of the important properties of these test methods.

Table1: Comparison of surfacing impact test methods

Test Methods	F1702	F355-A F1936	F1292	F1292 EN1177
Missile				
Shape	Cylinder	Cylinder	Head-form	Hemi-sphere
Mass (kg)	2.25	9.10	5.00	4.60
Diameter (cm)	5.0	12.8	~16.0	17.6
Impact Test				
Drop Height (m)	0.46	0.61	Variable	
Velocity (ms^{-1})	3.0	3.5	Variable	
Energy (J)	10.2	55.0	Variable	
Example Scores *(same sample of artificial turf)*				
Energy (J)	10.2	55.0		54.0
g_{max}	80	118		251
SI		423		1630
HIC		354		1364

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. Table 1 includes examples of scores from tests performed on the same sample of artificial turf. The measured g-max scores range from 80 g to 251 g. The HIC score from

an F1292 test was almost 4 times that recorded during an F355-A test performed at approximately the same impact energy.

Impact tests and impact simulation

Each of the impact tests described has some value as a relative measure of shock attenuation performance. But in order to have value as an estimator of an injury risk, the impact test must simulate the events that present that risk. To be a good simulator the test should mimic the structure (mass, shape, stiffness) and dynamics (impact velocity and impact energy) of those events.

The ASTM F1292 test method is intended to simulate the impact between a child's head and the surface. The hemispherical missile or headform used in this test approximates the mass and gross geometry of a child's head. The missile is dropped from a height equivalent to that of a playground structure so the impact velocity of the test also has good face validity.

The F355-A test method is used to test both natural and artificial turf football fields. The impact energy (54 Joules) and other parameters of the test are based on *in-vivo* head acceleration data from a study of middle linebackers (Reid et al, 1971). More recently, McIntosh et al (2000) found that concussion-inducing impacts experienced by Australian Rules Football players had a mean impact velocity of approximately 4 m s^{-1} and an impact energy of 56 Joules; values that are very close to those generated by an F355-A test (Table 1). The geometry and inertial properties of the F355-A missile do not represent those of the human head, however. The differences in missile shape, curvature, mass and impact velocity between the two methodologies have known effects on test outcomes. For simple surface properties, these effects can be predicted using the theory of contacting surfaces (Johnson, 1985) and nonlinear impact models (Shorten and Himmelsbach, 2002). The flat, circular face of the F355-A missile compresses the surface beneath it in a uniform and

linear manner. In contrast, the hemispherical missile or headform focuses the initial impact loads on a small area of the surface. The contact area increases as the missile penetrates the surfaces, introducing a non-linearity into the dynamics of the impact.

In addition to differences in raw test scores, it can be shown that the cylindrical missile introduces a bias in test results on thin, soft surfaces. A curved head, headform, helmet, or hemispherical missile tends to penetrate such surfaces, bottoming them out before they can effectively absorb the impact. The cylindrical missile engages more surface area and applies a more uniform pressure, allowing the impact energy to be absorbed before the thin, soft surface bottoms out.

While the hemispherical or head-shaped missile would appear to be a better simulator of a head impact, it is still limited as a predictor of head injury risk. The real human head has some flexibility, which can help it absorb some impact energy. A rigid headform does not have the same energy absorbing capacity and, as a result, produces higher g_{max} and HIC scores than a real head.

Estimates of Head Injury Risk

In order to estimate head injury risk from impact test data, the test scores must be adjusted to compensate for differences between the dynamics of the impact test devices and the human head. As an example we can consider the results of impact tests on three different kinds of turf surface. Figure 3A shows the typical range of g_{max} scores from F355-A test of well-maintained natural turf, newly installed conventional synthetic turf (carpet over a foam pad) and newly installed, infilled synthetic turf. (Surface conditions are emphasized because maintenance and aging can cause test results to vary markedly.) All would be considered to be performing in a "safe" range because the g_{max} scores are well below 200g (which closely approximates a HIC score of 1000 HIC on this test).
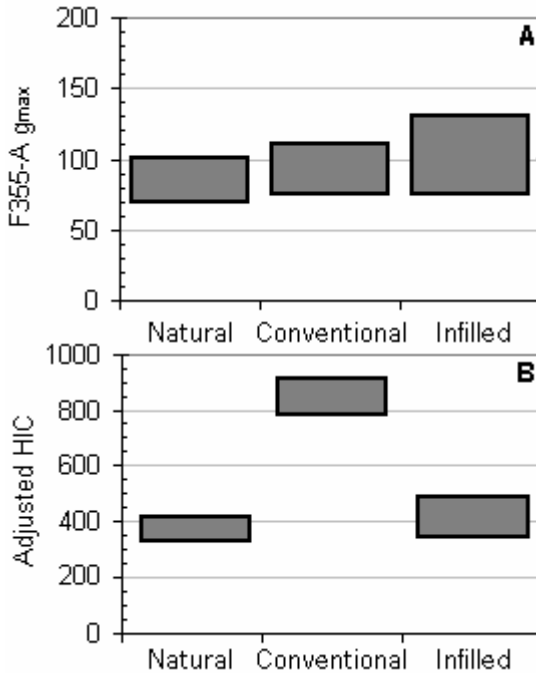
Fig. 3: (A) Typical range of g_{max} scores from 54 Joule, F355-A impact test of three types of turf surface.
(B) HIC scores from on the same surfaces at the same impact energy but using a rigid F1292 headform, and adjusted to cadaver-equivalent scores.

However, once the scores are adjusted to the HIC score from an equivalent test using a helmet-less cadaver head or biofidelic headform with the same impact energy, a different picture emerges. With the F355-A test's bias in favor of thin, soft surfaces removed, the conventional synthetic turf surface generates higher HIC scores than natural turf and infilled synthetic turf. Although the typical "adjusted" HIC scores remain in the non-fatal range for a 54 Joule impact, the conventional turf would appear to carry a higher risk of head

injury. This observation may help to explain why Guskeiwicz et al (2000) observed a five times greater risk of Grade II MTBI among football players exposed to artificial turf surfaces.

Surface design considerations

Shock attenuation

The principles underlying the influence of surface material properties on shock attenuation performance have been described by Shorten and Himmelsbach (2002). From the perspective of shock attenuation, the important properties of surfacing materials are thickness and stiffness or compressibility. In combination, these properties determine the energy absorption capacity of the surface and whether it can absorb the energy of an impact without bottoming out.

Thinner surfaces must be stiffer (less compressible) in order to absorb the same amount of energy as thicker, softer surfaces, but are more likely to produce higher impact accelerations. For any given impact energy, there is a minimum surface thickness that can accommodate the impact without bottoming out; a minimum that is independent of surface material properties.

The non-linearity of a surface's stiffness properties is also an important factor. If surface thickness is unlimited, surfaces that become less compressible as the load on them increases tend to have higher g_{max} scores but lower HIC scores. Loose fill playground surfacing materials typically reach 200g before producing a HIC of 1000. Conversely, surfacing materials or structures that buckle or soften when compressed tend to have lower g_{max} scores but higher HIC scores. Typically, unitary rubber/urethane surfaces score 1000 HIC before reaching 200g.

In a more realistic realm where there is a limit on the thickness of the surface, the best shock attenuation properties arise when the compression of the surface is maximised during an impact. Surfacing systems that buckle when loaded are most

efficient in this context. The thinnest possible surface that can meet any given shock attenuation criterion is always one the buckles or softens under load, rather than one that hardens as it is compressed.

Other design considerations:

Reducing risk of head injury is not the only performance issue that designers of sports surfaces must resolve. The frequency of lower extremity injuries has also been linked to surface properties. Excessive resistance to rotation between the shoe and the surface is a known risk factor in the aetiology of knee injuries, for example. Excessive traction may also contribute to the occurrence of diffuse head injuries under some circumstances (Camacho et al, 1999).

Ball bounce and roll, athlete performance, fatigue and perception are also important design considerations. In some instances (e.g. court sports), sports would be unplayable if the surface was compliant enough to absorb a major impact. Typically, athlete behaviour in these contexts is such that there is a low risk of collision between an athlete's head and the surface.

Discussion

The risk of head injury is an important concern in the design of sports surfaces. Catastrophic head injuries have life changing, even life-threatening consequences.

Evaluating the risk of head injury in any sport is a complex task. The context in which the injury might occur is an important factor because the probability that the athlete's head will strike the surface with sufficient energy to cause an injury varies from sport to sport. Football presents a higher risk of head to surface contact than court sports, for example. There is also the question of "acceptable risk" - how much risk are the athletes, coaches, parents and the watching public prepared to accept? Participants in sports (unlike the victims of motor vehicle accidents, for example) choose to expose

themselves to potentially hazardous situations. Participants in more aggressive contact sports would be appear to be more risk tolerant in this regard. Finally, an individual's susceptibility to injury will also vary, perhaps most significantly with his or her personal history of previous head trauma.

The shock attenuation of a sports surface is therefore only one factor in the overall development of head injury risk. The problem of determining this risk component directly from the results of standard impact test remains largely unresolved. Historically, g_{max} scores of 200 g and HIC scores of 1000 have been considered the acceptable limit on surface shock attenuation performance. The link between the test score limits and the cadaver impact data on which they are based in tortuous. However, our preliminary research in this area suggests that the conventional limits offer an appropriate level of safety, providing the surface is capable of absorbing the impact of a head without bottoming out. Infilled-turf surfaces, most playground surfacing and gymnastic crash mats, for example, meet this requirement. Conventional artificial turf is one example of a class of surfaces that typically cannot absorb the impact of a head without producing high g_{max} and HIC scores.

While severe head injuries to athletes are, fortunately, rare occurrences, recent research suggests that apparently "mild" head traumas, and especially a series of such minor concussions can have long term, negative effects on cognitive function. As current studies of head injury in sports are expanded, it is probable that the head impact-specific shock attenuation properties of sports surfaces will assume greater importance and become a focal point of further research.

Referenced Standards

ASTM F355 Standard Test Method for Shock-Absorbing Properties of Playing Surface Systems and Materials. ASTM International, West Conshohocken PA, USA.
ASTM F1292 Standard Specification for Impact Attenuation of Surface Systems Under and Around Playground

Equipment. ASTM International, West Conshohocken PA, USA.

ASTM F1936 Standard Specification for Shock-Absorbing Properties of North American Football Field Playing Systems as Measured in the Field. ASTM International, West Conshohocken PA, USA.

ASTM F1702 Standard Test Method for Measuring Shock-Attenuation Characteristics of Natural Playing Surface Systems Using Lightweight Portable Apparatus. ASTM International, West Conshohocken PA, USA.

EN1177 Impact absorbing playground surfacing - safety requirements and test methods. European Committee for Standardization, Brussels, Belgium.

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