Estimated Risk of Head Injury on Artificial Turf Surfaces with Brock Underlayment

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Summary

This report describes estimates of the head impact injury risk associated with new and aged infilled artificial surfaces with and without Brock underlayment.

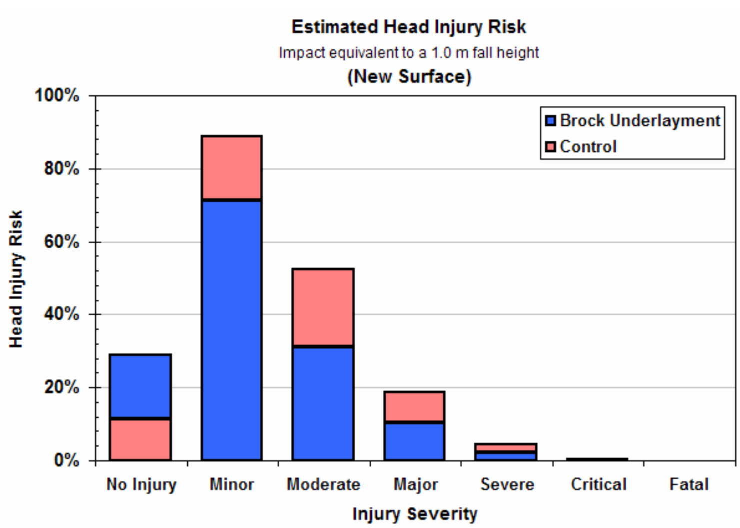
The estimates are based on the results of standard tests of artificial turf surfaces. The tests were performed on new surface samples and on surfaces subject to both simulated and natural aging.

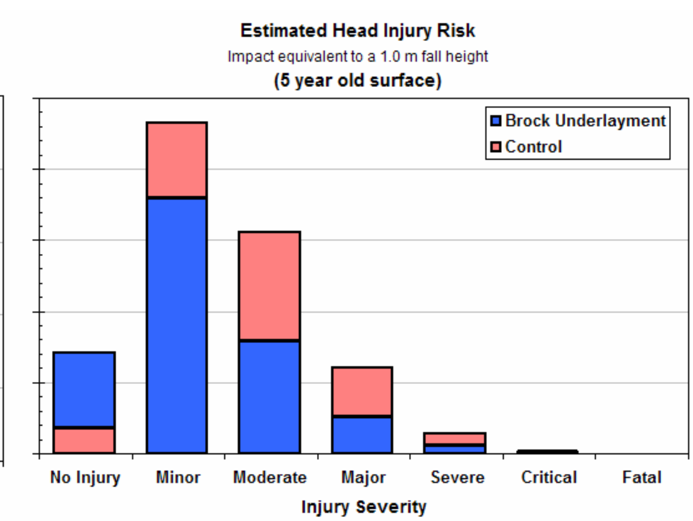
The impact tests themselves are not directly predictive of head injury risk. Consequently, in order to estimate risk, head injury criterion (HIC) scores from impact tests using rigid hemispherical missiles and a fall height of 1.0 m were converted to their equivalent values for biofidelic headforms. The converted HIC values were them compared with the injury risk curves derived from experiments on human cadavers (Prasad and Mertz, 1985).

The computed estimates show that a head impact equivalent to a fall from 1.0 m onto an infilled artificial turf surface has a low probability (< 0.5%) of producing a critical or fatal head injury. However, the probability of an injury-free impact is also small. Statistically, 9 out of 10 such impacts would be expected to produce a minor concussion or more brain severe trauma.

The addition of an impact attenuating Brock underlayment to the artificial turf surface increased the estimated probability of a non-injurious outcome from 11% to 29% and significantly reduced the estimated risk or minor, moderate and major head injuries.

Similar estimates for 5-year old surfaces showed a somewhat larger effect of the underlayment, directly attributable to the faster deterioration of impact attenuation performance of surfaces without underlayment.





Background

Sports are a common venue for head and brain injuries, to the extent that the US Centers for Disease Control and Prevention once considered the incidence of sports-related mild traumatic brain injuries (MTBI or “concussions”) to have reached epidemic proportions (CDC, 1977). Sports also present a risk of more severe, potentially life-threatening head trauma.

Since head injuries are probably the most traumatic possible outcome of an impact between an athlete and a surface, standard test methods used to evaluate the impact attenuation of sports surfaces are often linked to indices of head injury risk. For example, US standards for playground surfacing (ASTM F1936) specify performance limits using a head injury criterion (HIC). Similarly, impact attenuation specifications for football fields (ASTM F1936) are hypothetically linked to the non-fatal acceleration tolerance of the head.

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Surfaces as a Risk Factor

While it is a reasonable assumption that head-surface impacts are potentially injurious and that impact attenuating surfaces could reduce the frequency and severity of injury, 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, there is strong circumstantial evidence to support both the risk potential and the benefits of impact attenuating surfaces:

- 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).
- The risk of serious head injury following a fall is 1.7 times greater on a grass surface than on sand with greater impact attenuation (Laforest et al, 2000).

Other studies have compared the injury risk posed by natural turf and 1st Generation artificial turf[1]:

- While Clarke et al (1978) found no difference in the incidence of MTBI between natural and (1st Generation) artificial turf, Naunheim et al (2002) suggested that the risk is higher on artificial turf.
- More persuasively, Guskeiwicz et al (2000) 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 (1st Generation) 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 – equivalent to a five times greater risk of Grade II MTBI on artificial turf.

Since both “natural” and “artificial” turf systems encompass a wide range of surface properties the particular characteristics that caused the observed differences in head injury incidence remain unknown.

[1] “1st Generation artificial turf” includes older types of artificial turf consisting of a short-pile carpet, usually with a foam backing material but without granular rubber infill (e.g. “Astroturf”).

First generation artificial surfaces are no longer installed, and most have been replaced. Epidemiological studies have yet to assess the relative risk posed by newer generations of artificial turf, specifically infilled turf surfaces. However, Shorten and Himmelsbach (2003) used the results of impact attenuation tests and data describing the injury tolerance of the human head to estimate the relative risks posed by natural turf, 1st generation artificial turf and infilled artificial turf. Their results suggest that natural infilled surfaces have similar injury risk while 1st generation turf poses a substantially higher risk a finding that potentially explains the epidemiological results reported by Guskeiwicz et al (2000).

Impact Tolerance of the Human Head

Early experiments on head impact tolerance using human cadavers and animal models (Gurdjian et al, 1945, Gurdjian et al, 1955) resulted in 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 (Figure 1). 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.

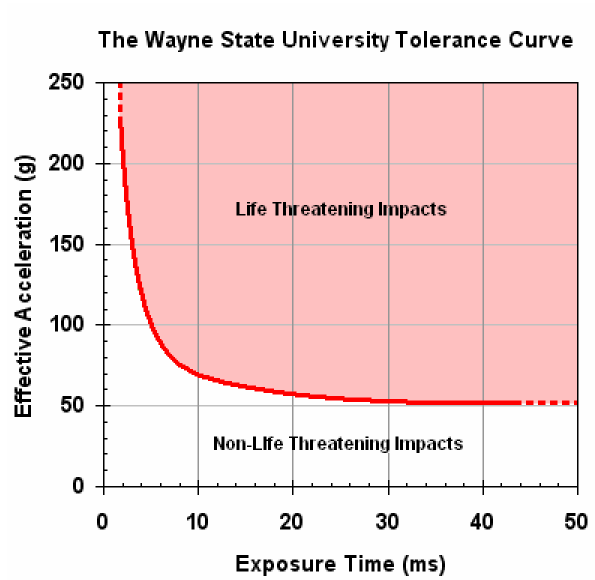


Figure 1: The Wayne State University Tolerance Curve. Head impacts with combinations of acceleration magnitude and exposure time lying above the tolerance curve are likely to result in injury.

Gadd Severity Index

Gadd (1966) observed that for a given degree of injury, the logarithmic slope of the tolerance curve is approximately -2.5 and proposed the Gadd Severity Index (SI) as a measure of the injury potential of an impact.

SI (Eqn. 1) is the integral of the impact's acceleration time curve, weighted by the 2.5 exponent observed in the Wayne State Tolerance Curve.

$$SI = \int_0^T a^{2.5} dt \qquad (1)$$

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 2B). An SI score of 1000 approximates the limit of human tolerance. Impacts with a higher score have a nonzero probability of causing a life-threatening brain trauma.

The Head Injury Criterion (HIC)

Practice has shown the Gadd Severity Index SI to be a useful predictor of the injury potential of impacts that produce focal brain injuries. However, for impacts of lower intensity but longer duration, the SI calculation tends predict more sever injuries than those observed in cadaver experiments. The Head Injury Criterion (HIC) is an alternative measure of head impact severity that is not subject to these errors. The HIC calculation (Eqn. 2) is similar to SI in principle but uses only that portion of the acceleration-time pulse that yields the highest score.

$$HIC = \max\left((t_1 - t_0)\left[\frac{1}{(t_1 - t_0)}\int_{t=0}^{t_1} a_t\right]^{2.5}\right) \qquad (2)$$

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 2.5^{th} power (Fig 2B) weights the accelerations according to head injury risk using Gadd’s method; deemphasizing 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 maximizes 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 and 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.

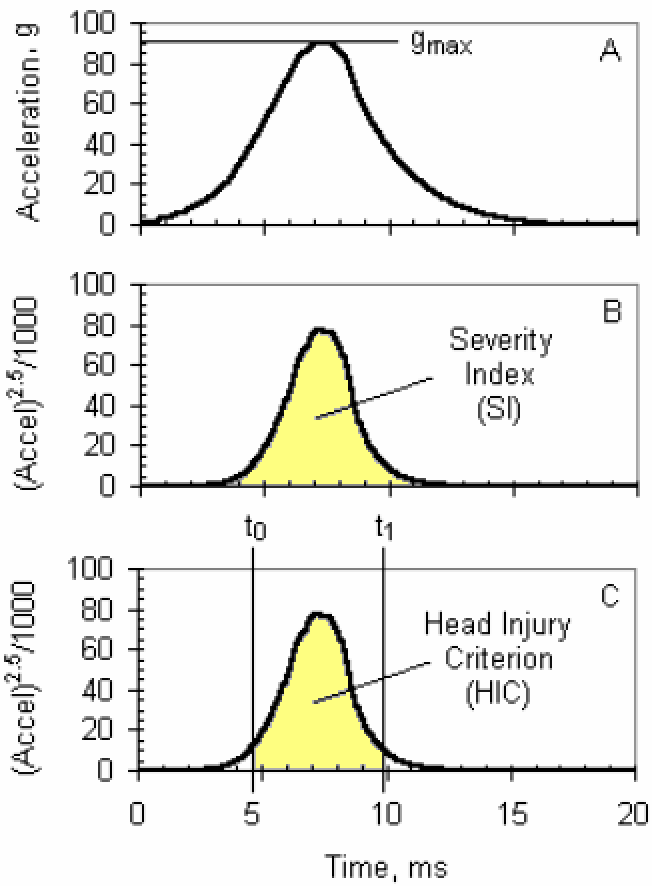


Figure 2: Example SI and HIC Calculations.

(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 by 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 and 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 3 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.

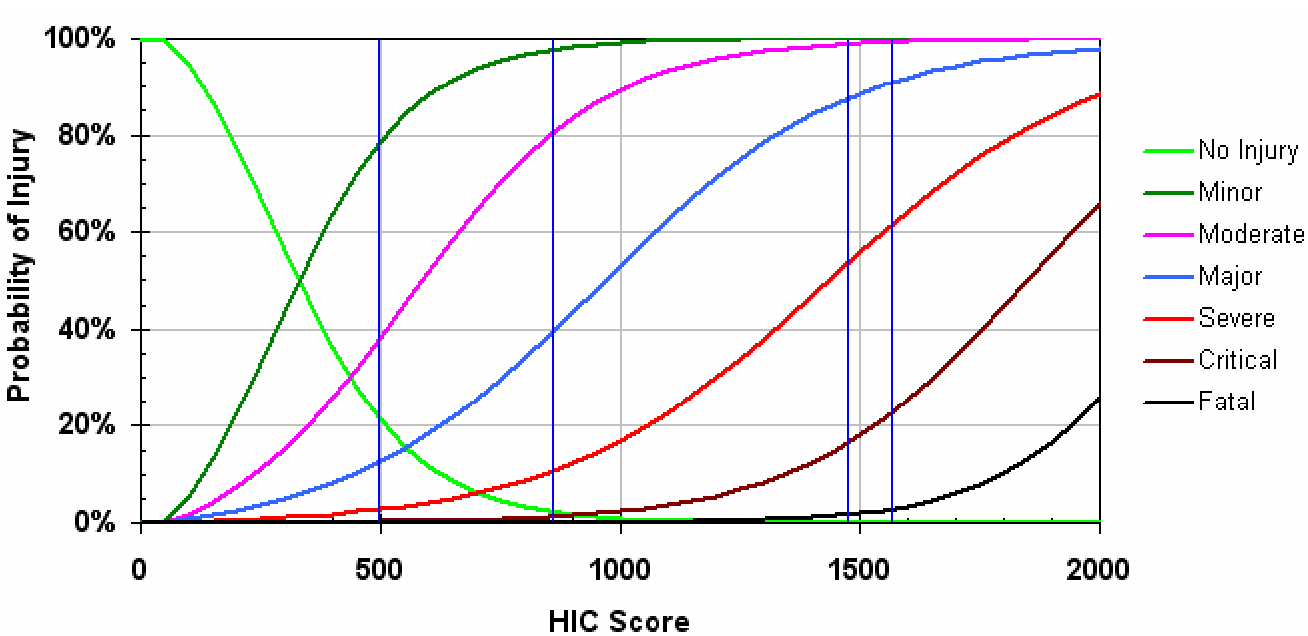


Figure 3: Expanded Prasad-Mertz Curves.

The curves show the relationships between the HIC score of a head impact and the probability of injuries of different severity

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 head 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%.

Brock Underlayment and the Impact Attenuation of Artificial Turf

Test results from this and other laboratories have shown that the use of a Brock underlayment between an infilled artificial turf surface and the substrate improves impact attenuation performance on standard tests. Figure 4, for example, shows the results of laboratory tests comparing the impact attenuation of three surface–underlayment combinations by means of the ASTM F355-A (ASTM F1936) method. Compared with no underlayment, two Brock underlayments reduced peak impact shock (*g*-max) by ~28 and ~40% respectively (Shorten and Himmelsbach, 2007). Using the same test method, Ramsay and Nixon (2008) similarly found ~29% reduction in *g*-max comparing an infilled turf sample with and without a Brock Performance Base F24 ("Powerbase") underlayment.

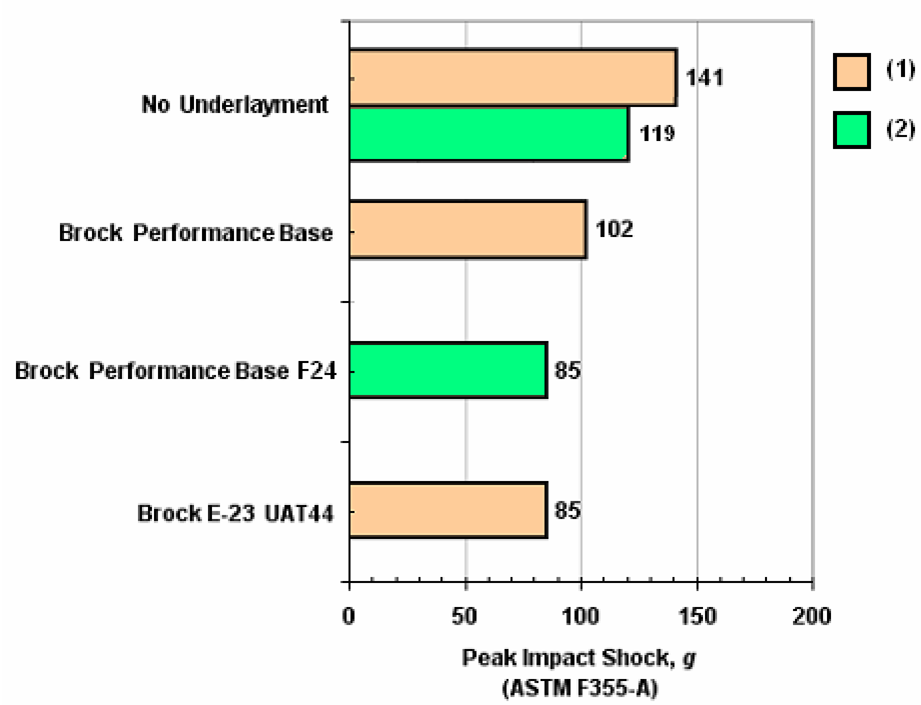


Figure 4: Peak impact shock (*g-max*) scores of new infilled turf surfaces with no underlayment and with various Brock underlayments. [ASTM F355-A test method; from (1) Shorten and Himmelsbach, 2007 (2) Ramsay and Nixon, 2008]

Effect of Aging on Impact Attenuation

Ramsay and Nixon (2008) report the results of *simulated* surface aging on the impact attenuation of infilled artificial turf surfaces with and without a Brock underlayment. For an infilled turf field, their results show *g*-max scores increasing from a "new" value of 119 *g* to over 200 *g* after two years of simulated use and to 237 *g* after 10 years. In contrast, a similar surface with Brock underlayment did not exceed 100 *g* after 10 years of simulated use (Figure 5 A).

Since 200 *g* is the F1936 performance limit commonly used to specify filed performance in construction contracts and warranties these data suggest that infilled turf fields without underlayment "fail" only two years after installation. Our experience from tests of several hundred sports facilities in North America suggests that installed infilled turf system age at a different rate from that observed under simulated conditions (Figure 5 B). While the "new" scores are similar, we see g-max scores increasing to an average of 160 g after two years and plateauing around level until five years post-installation.

The impact attenuation of an infilled turf surface appears to deteriorate more rapidly during the laboratory simulation that in the field. It is reasonable to expect the simulation probably wears the surface with underlayment more aggressively, too, but there is insufficient data from field installations with Brock underlayment to confirm that this is so.

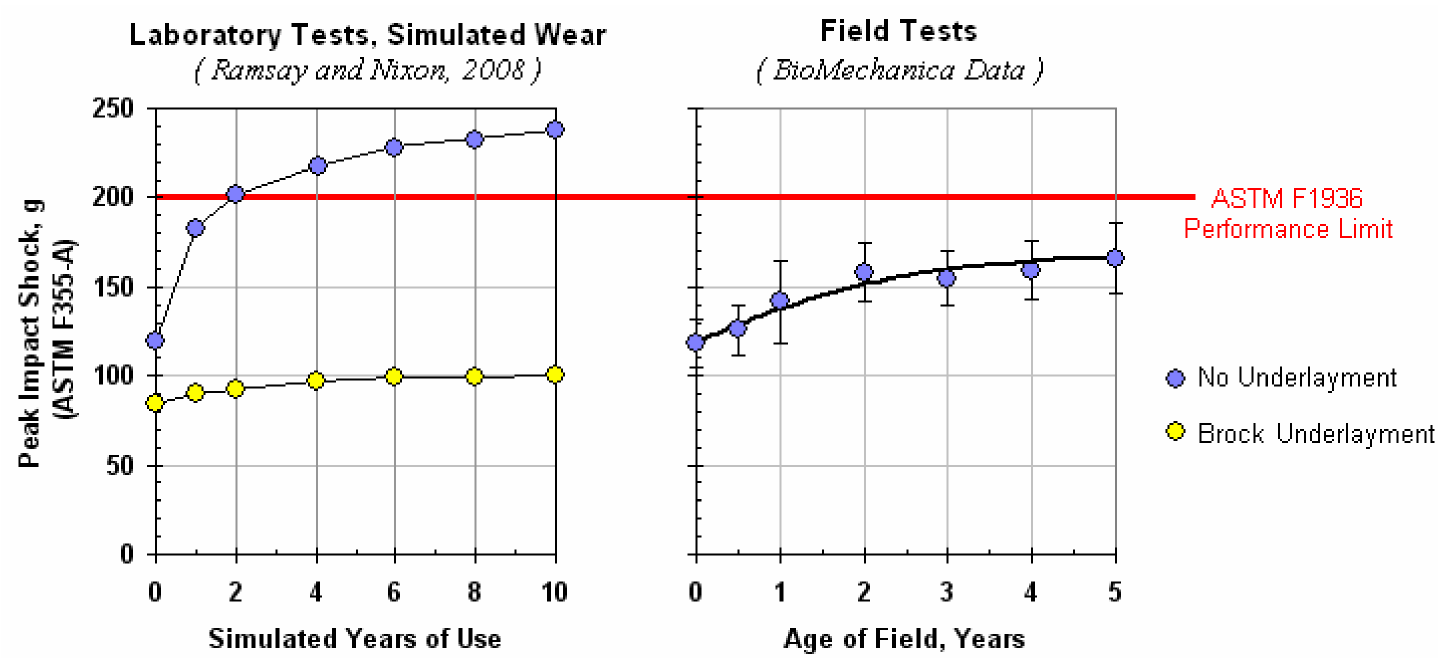


Figure 5: Effects of Aging on Impact Attenuation of Infilled Turf Surfaces

A: Results of simulated aging tests

B: Results from impact tests of installed surfaces (Mean ± sd; total sample size n = 103)

Estimation of Head Injury Risk

Using data from impact tests of surfaces, it is possible to estimate the risk of head injury. However, the analysis is not a straightforward conversion of HIC scores to injury risk. Some complicating factors must also be considered.

- The Head Injury Criterion and Prasad-Mertz risk curves are based on data for the human head. While they are also assumed to be valid for impact tests with biofidelic headforms, they are not applicable to the outcomes of impact tests with the rigid missiles used on most tests, nor to any impact tests with missiles having geometry and inertial properties that differ significantly from those of the human head.
- Shorten and Himmelsbach (2003), for example, found that the ASTM F355-A test method (which employs a rigid cylindrical missile) significantly distorts the relative injury risks imposed by 1st generation artificial turf, infilled turf and natural turf. Based on *g*-max scores alone, test results would favor 1st generation turf. However, the flat cylindrical face of the F355-A missile does not penetrate thin surfaces in the way a headform or human head would and consequently is biased in favor of thin, soft surfaces. A more robust estimate of injury risk found that 1st generation turf surfaces offered substantially less protection than both infilled artificial turf and natural turf.
- Assuming, a rigid impact test missile’s mass and geometry mimic those of the head, a rigid missile does not simulate the head’s elasticity (Saczalski, et al, 1976). The human skull is jointed and slightly flexible – elastic in way that contributes to impact attenuation. Consequently, a rigid missile or headform produces results that tend to overestimate the risk and severity of potential injury outcomes. Such conservative estimates are acceptable in specifications for protective surfaces, but not so if a “true” estimate of injury risk is required.
- The data on which the Prasad - Mertz Curves are based on data from adult cadavers subjected to frontal head impact. The extent to which this data is valid for athletes experiencing non-frontal impacts to the head is not known.

In order to make a “fair” estimate of injury risk from impact test data, some caution must be employed:

- Preferred sources of raw data are test result using missiles with geometry and mass approximating those of the human head (e.g. spherical or hemispherical impact surfaces, 4 – 7 kg mass)[2].
- Test results need to be corrected for the inertia and elasticity differences between the human head and the rigid missile.
- Adjusted HIC scores may used to *estimate* risk from the Prasad-Metz curves. Even so, the outcomes of the analysis should be interpreted cautious since they are the outcome of a mathematical process, not that of a biofidelic test or an epidemiological study.

[2] Alternatively, mathematical models must be used to determine surface material properties from acceleration time data produced by, say , an F355-A missile and then to calculate the results of an impact between a human head or headform surrogate and a surface with those properties.

Calculations

The following calculation steps were used estimate the head injury risk associated with impact test results.

Data Sources

- For new surface samples with and without Brock underlayment, the EN 1177 HIC scores reported by Ramsay and Nixon (2008) were used as the primary data source. These results are consistent with our own observations in the laboratory and in the field.
- For aged turf samples, Ramsay and Nixon (2008) provide impact test results from a simulated aging protocol. Comparing these results with our observations of the aging of surface installations suggests the aging protocol is somewhat more aggressive. For simulated 5-year old fields, Ramsay and Nixon (2008) report an EN1177 HIC score of 1500 at a 1m fall height and an ASTM F355-A *g*-max score 229 *g*. Our field tests of 5 year old installations show a lower *g*-max averaging 165 g; equivalent to a EN 1177 HIC score (1.0 m) fall height of ~1050.
- No field data for aged surfaces with Brock underlayment are available. While the simulated aging protocol probably accelerates surface degradation as it appears to in surfaces without underlayment, the data provided by Ramsay and Nixon (2008) were assumed.

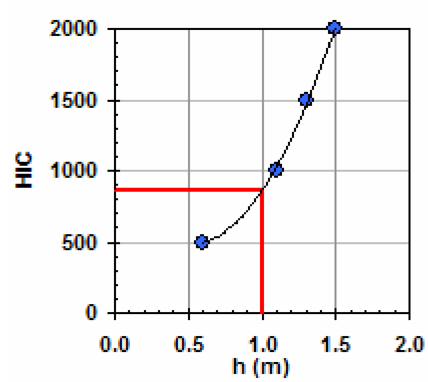
The use of field equivalent data for aged surfaces without underlayment and simulated aging data for surfaces with Brock underlayment is a deliberately conservative choice – one that tends to reduce the effects of the underlayment and reduce the likelihood of overestimating its potential benefits.

Fall Height

The analysis assumes an impact equivalent to a fall height of the 1.0 m – a standard employed by some sports federations. It is also a conservative choice since differences among surfaces would likely be greater at higher fall heights.

HIC Scores

Data from the EN 1177 impact tests reported by Ramsay and Nixon (2008) were interpolated where required to estimate a 1.0 m HIC score. The example at right shows the interpolation of a 1.0 m HIC value of 860 for a new surface without underlayment.



Biofidelic HIC

HIC scores were adjusted for the differences between biofidelic and rigid headforms using the data of Saczalski, et al (1976).

This step reduces the HIC scores by between 10 and 35%, with higher values reduced by greater percentages than smaller ones. Consequently, the calculation also reduces a potential source of error that would tend to overestimates the effects of surfaces and the differences among them.

Injury Risk Estimates

Estimated injury risk associated with the adjusted HIC scores were determined from the Expanded Prasad-Mertz Curves (Prasad and Mertz, 1985)

Results

Surface		Impact Test Results and Calculations						Prasad-Mertz Injury Risk						
		F355-A	EN 1172*		Biofidelic*		Injury		AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	
		g-max	HIC	g-max	g-max	HIC	Severity*	No Injury	Minor	Moderate	Major	Severe	Critical	Fatal
New	Control	119	860	127	104	604		11%	89%	52%	19%	4%	0%	0%
	Brock	85	492	97	89	444		29%	71%	31%	10%	2%	0%	0%
							Δ	18%	18%	21%	9%	2%	0%	0%
							Rel Risk	0.39	1.25	1.69	1.85	1.93	2.23	2.78
							$(\text{Rel Risk})^{-1}$	2.55	0.80	0.59	0.54	0.52	0.45	0.36
5 years	Control	165	1050	140	110	680		7%	93%	62%	24%	6%	1%	0%
	Brock	100	500	98	90	448		28%	72%	32%	10%	2%	0%	0%
							Δ	21%	21%	31%	14%	3%	0%	0%
							Rel. Risk	0.25	1.30	1.97	2.34	2.54	3.15	4.33
							$(\text{Rel Risk})^{-1}$	4.06	0.77	0.51	0.43	0.39	0.32	0.23

** 1.0 m fall height*

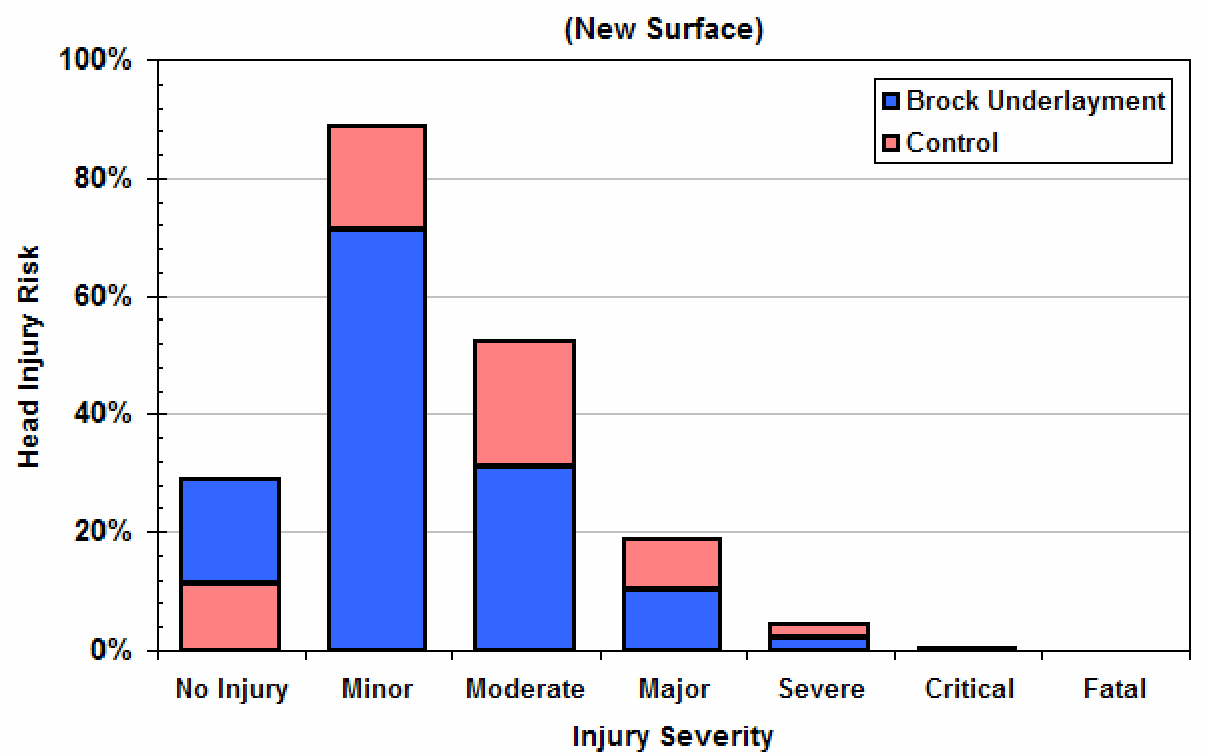
Δ — is the absolute difference in risk between the control surface and that surface with underlayment.

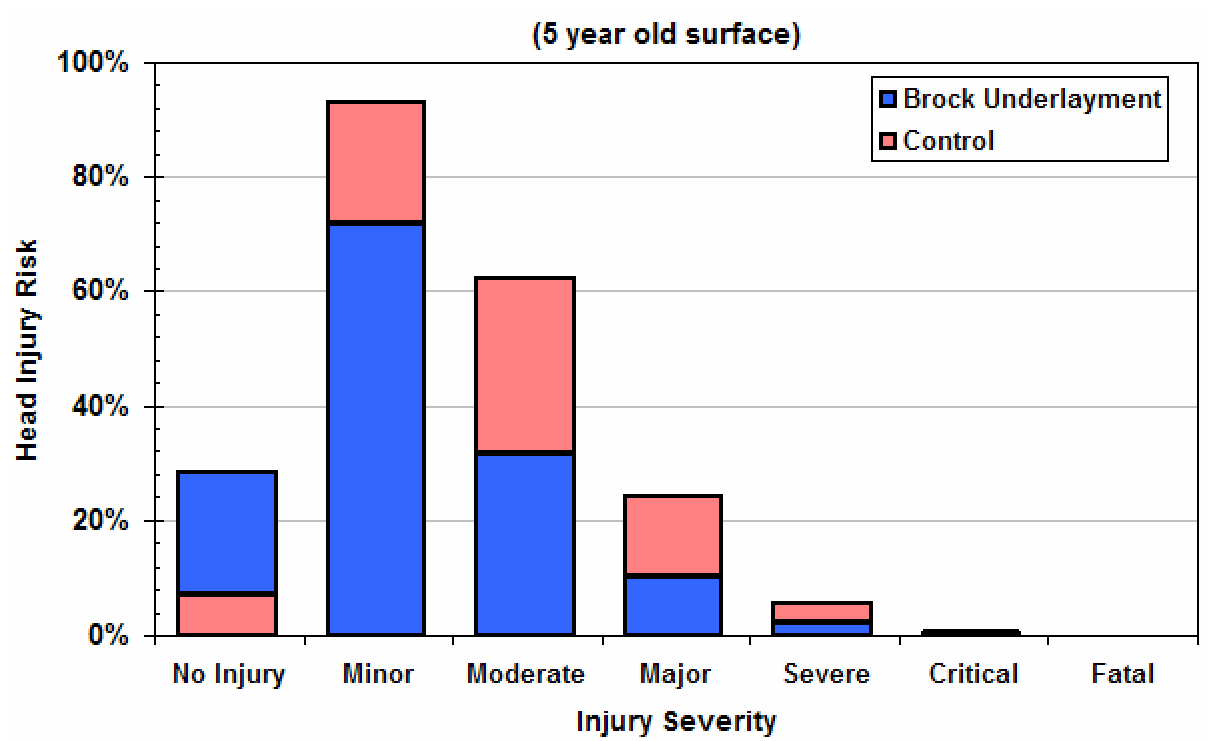
Rel Risk — is the “relative risk”, the ratio of the risk posed by the control surface to that of the surface with underlayment. A relative risk of 2.0, for example indicates that the probability of injury on the control surface is double that of the surface with underlayment.

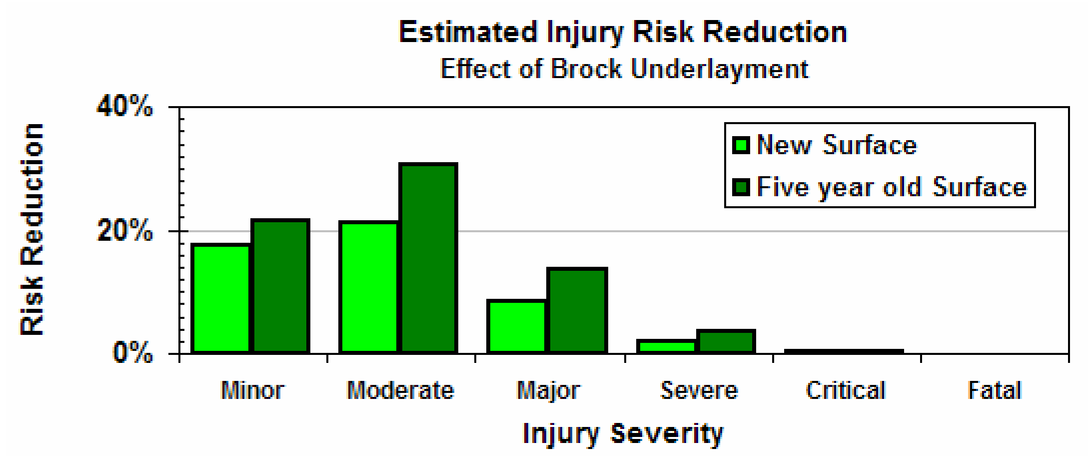
$(\text{Rel Risk})^{-1}$ — The inverse of the relative risk, i.e. the ratio of the risk imposed by a surface *with* underlayment to that of the control surface. An inverse relative risk of 0.5, for example, indicates that the probability of injury on the surface with underlayment is 50% of that on the control surface.

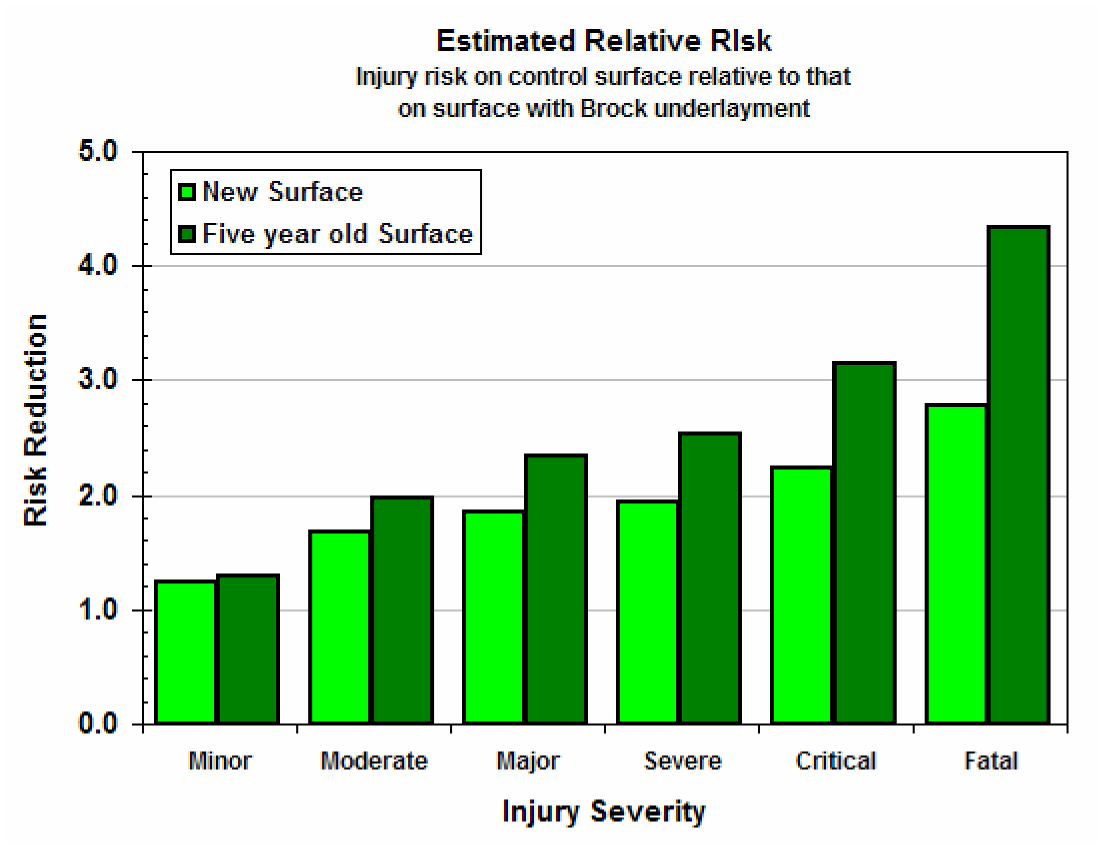
* See Appendix 1: Abbreviated Injury Scale

Estimated Head Injury Risk
Impact Equivalent to 1.0 m Fall Height






Estimated Injury Risk Reduction
Effect of Brock Underlayment
Risk Reduction
40%
20%
0%
New Surface
Five year old Surface
Minor
Moderate
Major
Severe
Critical
Fatal
Injury Severity


Estimated Relative RIsk
Injury risk on control surface relative to that
on surface with Brock underlayment
Risk Reduction
5.0
4.0
3.0
2.0
1.0
0.0
New Surface
Five year old Surface
Minor
Moderate
Major
Severe
Critical
Fatal
Injury Severity

Discussion

The computed estimates show that a head impact equivalent to a fall from 1.0 m onto an infilled artificial turf surface has a low probability (< 0.5%) of producing a critical or fatal head injury. However, the probability of an injury-free impact is also small. Statistically, 9 out of 10 such impacts would be expected to produce a minor concussion. The risk of more severe trauma is also significant. Moderate head injuries ((M)AIS Level 2) have an estimated probability of 52% and the risks of major (MAIS 3) and severe (MAIS 4) injuries are 19% and 4% respectively.

The addition of an impact attenuating Brock underlayment to the artificial turf surface increased the estimated probability of a non-injurious outcome from 11% to 29% and significantly reduced the estimated risk of minor, moderate and major head injuries.

While the absolute effects of the underlayment are greatest in the MAIS 1- MAIS 3 range, the effects on the relative risk of more severe outcomes is also of potential value. For example, the risk of a head impact equivalent to a 1.0m fall on a control surface having a fatal outcome is small (~ 0.01% or 1 chance in 10,000). The underlayment reduces this risk from 0.011% to 0.004%, a small absolute change but equivalent to a relative risk of 2.8 – i.e. a fatal injury would be 2.8 times more likely to occur on the control surface than on one with underlayment.

Similar estimates for 5-year old surfaces showed a somewhat larger effect of the underlayment, directly attributable to the faster deterioration of impact attenuation performance of surfaces without underlayment.

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ASTM F1292 Specification for Impact Attenuation of Surface Systems Under and Around Playground Equipment. ASTM International, West Conshohocken PA, USA.

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

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Appendix 1: Abbreviated Injury Scale

The Abbreviate Injury Scale (AIS) classifies head injuries according to a series of injury characteristics of ascending severity. The table below shows the characteristics that define each level of the injury scale.

Injury / Symptom	AIS Degree	1 Minor	2 Moderate	3 Major	4 Severe	5 Critical	6 Survival Uncertain
Headache, Dizziness							
Loss of Consciousness							
Skull Fracture							
Neurological Damage							
Hemorrhage							
Brainstem Damage							
Brain Tissue Disruption							

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