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Do playground surfacing standards reflect reality?

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Introduction

- ✓ **Principles of risk estimation for head injuries**
  - Background of 1000 HIC, AIS, …
  - Biomechanical principles (energy, bounce, …)
- ✓ **Threshold for hazards in Australia**
  - Fall related safety limits in standards (free height of fall, requirements for safety surfacing…)
  - Injury data and their consequences

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Defenestration in Prague 1618

- ✔ History records that in 1618 two Hapsburg Regents were thrown out a third story window and survived a fall of more than 20 m
- ✔ Catholics maintain the men were saved by angels, who caught them
- ✔ Protestants claim they fell into a heap of horse manure

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Principles of risk estimation for head injuries

- ✔ We use biomechanics to study the forces and their effects on the human body
- ✔ We also use biomechanics to understand and predict the mechanisms associated with injury
- ✔ The amount of stress is inversely proportional to the area over which a force is applied, thus a fall onto the edge of playground equipment will result in a concentrated force over a small area resulting in a greater stress
- ✔ Bones are flexible to a point, however, when the deformation exceeds the ultimate stress limit of the bone mechanical failure results and this is manifested as a fracture

Principles of risk estimation for head injuries

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The likelihood of fracture is dependent upon both extrinsic and intrinsic factors

✓ **Extrinsic factors**

- Include magnitude and direction of the force, rate of loading, and the area over which the force is distributed
- Factors such as properties of the IAS, height of fall, angle (vector) of fall, and the initial velocity (forced movement devices) all influence the loading

Principles of risk estimation for head injuries

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✓ **Intrinsic factors**

- Are the structural and material properties of the affected tissue
- Bones have non-homogeneous mechanical properties
- Things such as: the region of the bone, the direction the force is applied, type of bone, developmental age of the bone, the health of the bone all affect the mechanical properties

Principles of risk estimation for head injuries

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✓ **Types of head injuries**

- Head injuries can be classified under four primary sub-categories in relation to the injury, namely: scalp damage, skull fractures, extra-cerebral blending and brain damage
- Clinically brain injuries can be classified into two broad categories, namely: focal injuries (ie specific location) and diffuse injuries (ie over a more widespread area)

Principles of risk estimation for head injuries

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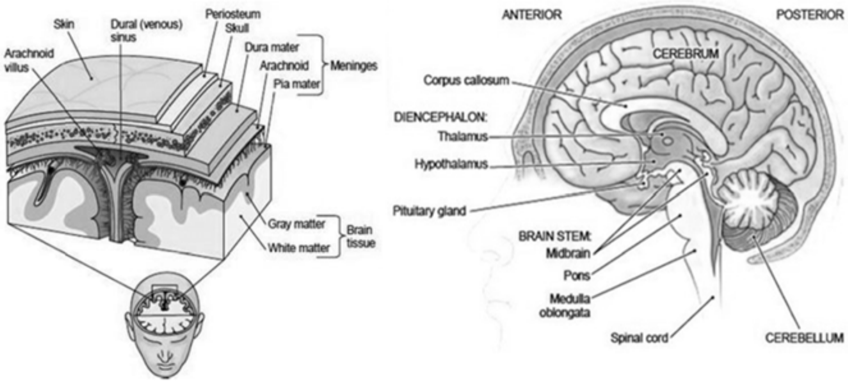

Anatomy of the head and brain

Principles of risk estimation for head injuries

- When the head is involved in a direct impact the skull is deformed
- Skull fractures occur if the skull is deformed beyond its loading capacity
- Bending of the skull can occur at the site of the impact or at a remote point
- The brain tissue is suspended within cerebral fluid within the skull
- Thus an impact to the skull also produces a pressure wave that travels through the brain tissue and suspending fluid
- Researchers have hypothesised that this pressure wave causes contusions remote to the impact site

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Principles of risk estimation for head injuries

✓ **Theories of brain injury mechanisms**

- Current theories of brain injury include: negative pressure, positive pressure, pressure gradients, and rotation and shear effects

✓ **Negative pressure**

- The primary component of negative pressure theory is cavitation
- Localised negative pressures create a vacuum cavity as the brain and/or meninges separate from the skull
- The subsequent collapse of this cavity results in tensile stresses and damage to the tissue

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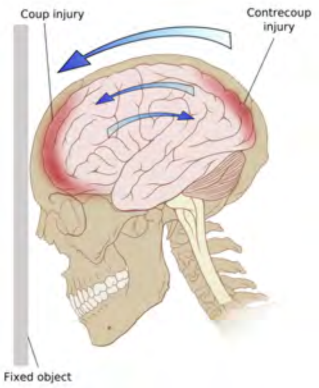
✓ **Positive pressure**

- Damage to the brain occurs in locations of positive pressure ie coup injuries when the head is impacted and contrecoup injuries during falls



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Principles of risk estimation for head injuries

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✓ **Pressure gradients**

- The pressure gradients create shear stresses which result in local deformations of the brain tissue
- The skull deformation causes a pressure gradient to flow from the area of high pressure to low pressure
- Research on impacted dogs suggests that injury occurs with both: short duration, high acceleration and high-pressure impacts; or long duration, low acceleration and low-pressure impacts

Principles of risk estimation for head injuries

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- ✔ **Rotation**
  - The brain's inability to rotate freely in the frontal compartment of the skull causes shear stresses and strain and leads to injury
  - Subdural hematoma has been observed from short duration, high amplitude angular accelerations
- ✔ **Current understanding**
  - The understanding of brain injury in children is limited
  - We know the range over which injury occurs is large
  - Current IAS simply limit or reduce the probability of injury to a level that the community is willing to accept
  - Societal cost is a complex trade-off that needs take into consideration the benefits of risk v cost of injuries

Principles of risk estimation for head injuries

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- ✔ In recent years research has confirmed that multiple 'brown out' concussions lead to dementia
- ✔ For generations we have known that boxers suffer from dementia
- ✔ When non-boxing athletes developed dementia it became apparent that repetitive 'softer' impacts to the brain were causing permanent damage
- ✔ What we now know is that when someone suffers an impact to the head, this injury takes time to repair and they should be protected (rested) from exposure for a time period commensurate with the magnitude of the impact and past history head impacts

Head Injury Criteria

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- ✔ The most commonly accepted global criterion for head impacts is the Head Injury Criterion or HIC
- ✔ The head is the part of the body we have traditionally used to measure injury in playgrounds
- ✔ What is the origin of the HIC?
- ✔ Is the 1000 HIC a good indicator of exposure to injury to children in playgrounds?

Head Injury Criteria

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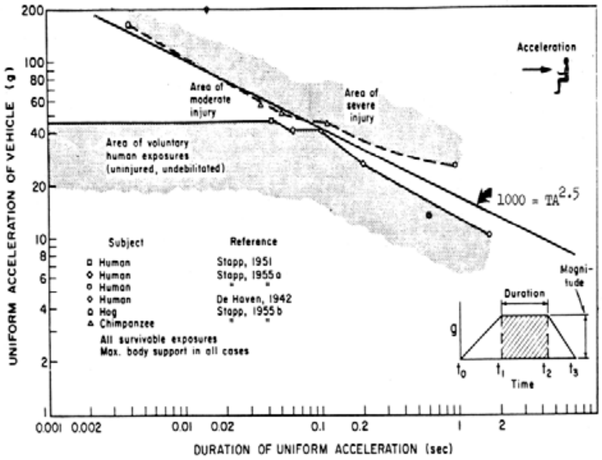
- ✔ Most injury criteria attempt to relate measured dynamic or kinematic input or output parameters to observed injury phenomena
- ✔ The methods are approximations of complex dynamic living systems being damaged by an external impact
- ✔ The original data were obtained from testing undertaken by the US Air Force and published by De Haven and Dubois (1942) and Stapp (1949-55)
- ✔ These tests were on humans, pigs and chimpanzees

Head Injury Criteria



Human tolerance to rapidly applied accelerations: A summary of the literature (Eiband et al., 1959)

Head Injury Criteria

- ✔ In 1966 Gadd proposed a criterion using the Wayne State University data. It is approximated by a straight line on this graph with a slope of 2.5 or $1000 = T.A^{2.5}$
- ✔ There are two things to note here:
  1. A straight line is not the only curve that could be applied to this data
  2. The slope of this line does not have to be 2.5
- ✔ A small change in the exponential results in a huge change in the HIC

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Head Injury Criteria

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- ✔ The majority of more recent research in head impacts has been conducted for motor vehicle safety
- ✔ Early work produced the Wayne State Tolerance Curve (WSTC) which defined the boundary between safe 'non-dangerous to life' and unsafe 'dangerous to life' head acceleration levels and formed the basis of Federal Motor Vehicle Safety Standard (FMVSS)
- ✔ Only six data points were originally used to graph the WSTC
- ✔ The WSTC has been extended using cadavers, animal impact data, dummies and human volunteers

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Head Injury Criteria

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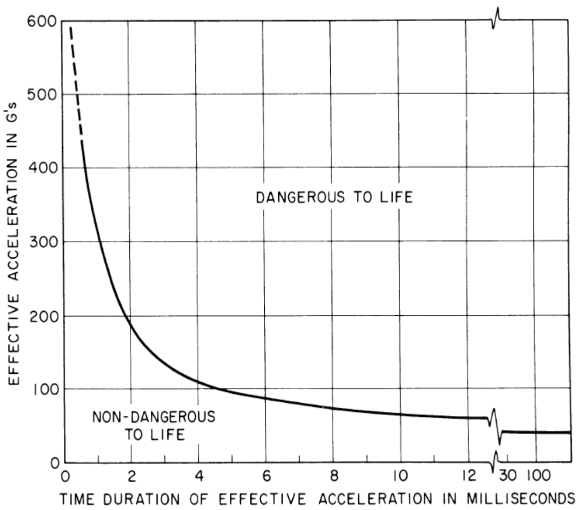

Wayne State Tolerance Curve

Head Injury Criteria

- There are a number of notable differences between the military data and the automotive data, namely:
  1. Military: acceleration of the seat that the subject rode on and acceleration was a rectangle/trapezoid pulse
  2. Automotive: acceleration was what the body of the subject experienced and was a rounded triangular pulse
- The rounded triangular pulse is more akin to what we measure in a playground IAS
- The rectangular pulse reflects what is observed on an amusement ride or rocket escaping earth's gravitational field
- The area under the two pulses is different ie a triangle is less than half the rectangle/trapezoid
- Neither use g_{max} , rather average or 'effective' acceleration

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Head Injury Criteria

- The WSTC depicts the boundary between a tolerable impact and an intolerable impact
- Any point on the curve represents the same threshold
- The WSTC infers that very intense head acceleration levels are tolerable if they are very brief
- The experiments used a direct head impact with a rigid, flat missile
- The head accelerations were measured with accelerometers placed diametrically opposite the impacted region
- The head impact data assumed that head injury was a function of linear head acceleration and impulse duration

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Head Injury Criteria

- ✔ Gadd argued that the average acceleration was not sufficient to accurately determine the response of the head to an impact
- ✔ The resulting injury potential is highly dependent upon the acceleration pulse and pulses with the same acceleration but different shapes can have different levels of injury
- ✔ Gadd proposed the Severity Index (SI) which involved integrating the acceleration pulse over its entire duration with an exponential weighting factor of 2.5 (based on the WSTC):

$$(G)SI = \int_0^T a(t)^{2.5} dt \qquad (a(t) \text{ in g's})$$

- ✔ A threshold for concussion for frontal impact was set at a severity level of 1000

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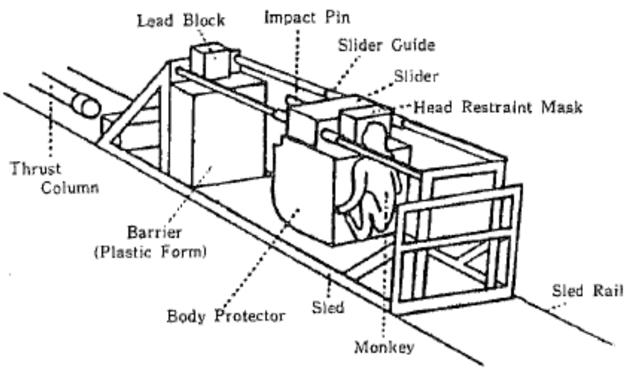
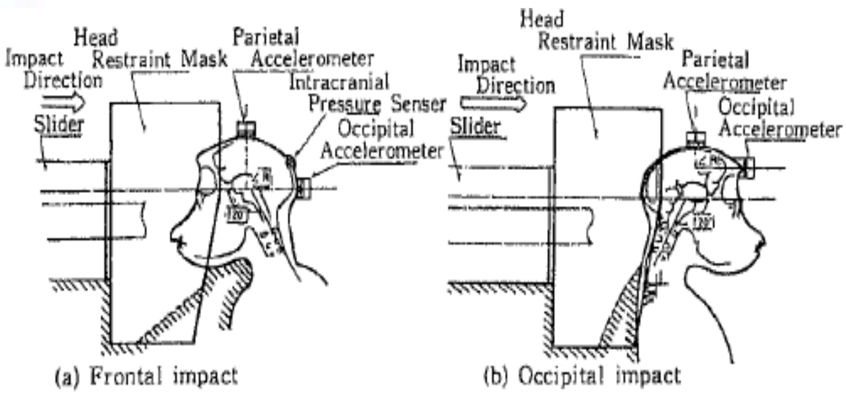
Head Injury Criteria



Sled used for translational impact of monkey head

JARI Human Head Impact Tolerance Curve (JHTC)

Head Injury Criteria



Translational frontal and occipital impact of monkey head

JARI Human Head Impact Tolerance Curve (JHTC)

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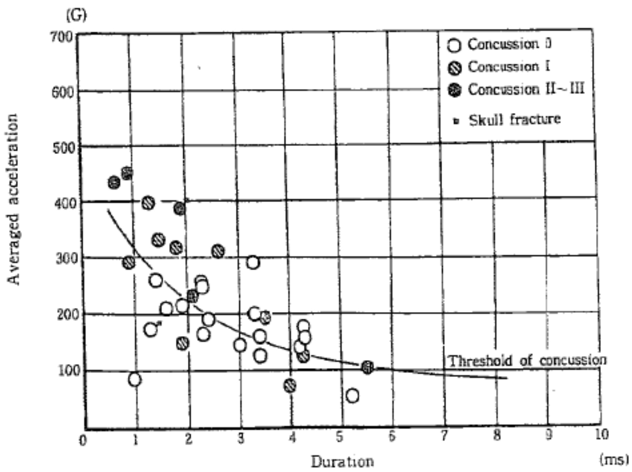
Head Injury Criteria



Threshold of concussion in humans extrapolated from averaged acceleration-duration by dimensional analysis in frontal impact of monkey head

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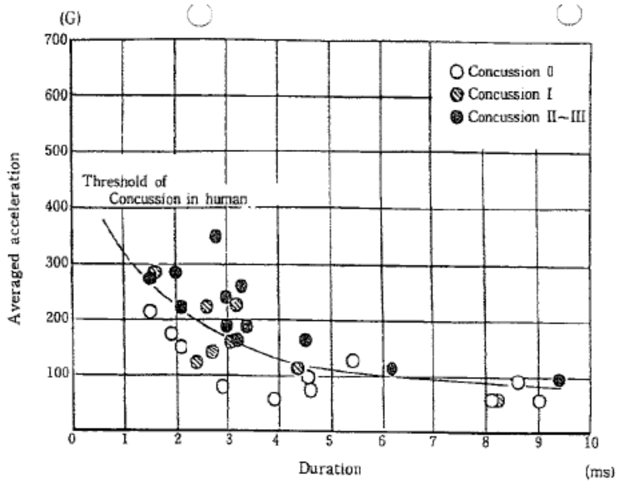
Head Injury Criteria



Threshold of concussion in humans extrapolated from averaged acceleration-duration by dimensional analysis in occipital impact of monkey head

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Head Injury Criteria

TOLERANCE THRESHOLD FOR HUMAN HEAD IMPACT - The authors obtained the concussion threshold curve for the monkey head and, using this as a basis, estimated the concussion threshold curve of the human head. Further, using human cadaver skulls they were able to experimentally determine the human skull fracture threshold curve.

In autopsies on monkeys which had shown concussion, subarachnoid and subpial hemorrhage were visible in 56% of all cases. Also, of the 45 monkeys which recovered from concussion, 12 showed brain contusions. This fact suggest that, from the clinical aspect, cases of slight lesions to the head which have previously been regarded as "concussion only" may include some cases of brain contusion, even if these do not present obvious symptoms. In fact, as one of the authors (N. N. et al.) previously reported[22], CT scanning has revealed brain contusions in 4-5% of cases clinically diagnosed as "concussion only."

Extract from SAE 801303 Report, Human head tolerance to sagittal impact reliable estimation deduced from experimental head injury using subhuman primates and human cadaver skulls

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Head Injury Criteria

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The human concussion threshold curve estimated in this study from that of monkeys, when considered in the light of these clinical cases, can be seen to represent a strict tolerance limit which tends towards the conservative side. The fracture threshold, as can be seen from the monkey experiments also, is a threshold indication at which there is a high probability of fatality. The human concussion threshold curve derived both from that of monkeys and from the human cadaver skull fracture threshold curve is shown in Fig. 24. This is taken to be the head impact tolerance curve for humans, and has been named the JARI Human Head Impact Tolerance Curve (abbreviated to JHTC).

Extract from SAE 801303 Report, Human head tolerance to sagittal impact reliable estimation deduced from experimental head injury using subhuman primates and human cadaver skulls

Head Injury Criteria

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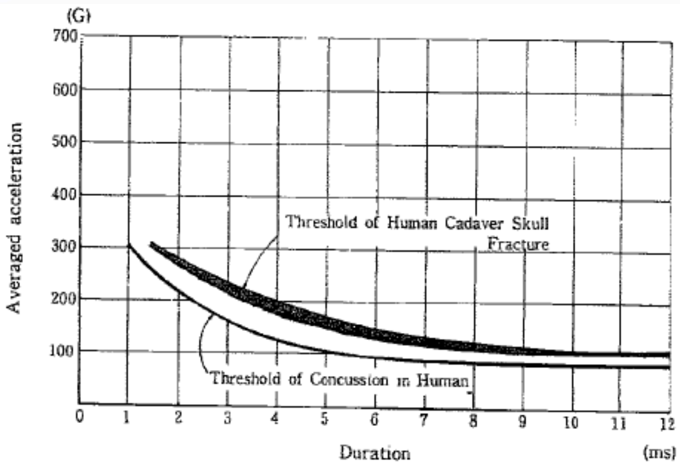

JARI Human Head Impact Tolerance Curve (JHTC)

Head Injury Criteria

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- ✔ A critique of the Severity Index led to the development of the Head Injury Criterion (HIC)
- ✔ The HIC is calculated by integrating the acceleration vs time curve over the time interval in which the HIC attains a maximum value:

$$\mathrm{HIC} = \left[\left(\frac{\int_{t_1}^{t_2} a\mathrm{d}t}{t_2 - t_1}\right)^{2.5} (t_2 - t_1)\right]\max$$

- ✔ The threshold of 1000 HIC was based on data for male adults sustaining translational impacts to the head
- ✔ It does not account for rotational motion and it does not relate to children

Head Injury Criteria

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- ✔ In the automotive industry the HIC maximization was historically calculated over 36 ms time interval
- ✔ More recently this was reduced to 15 ms to more closely match the hard contact impacts. It is abbreviated as HIC_{36} and HIC_{15}
- ✔ This refinement makes no difference to the impact we measure on IAS in playgrounds as we rarely record HIC durations exceeding 15 ms
- ✔ The US automotive industry HIC thresholds have been lowered
- ✔ ASTM is currently considering lowering the HIC and G levels where children

Principles of risk estimation for head injuries

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✓ Abbreviated Injury Scale (AIS)

- The AIS was developed in the mid-1960s as a system to describe the severity of injuries throughout the body
- It has a scale from 1 to 6, where:
  - 1 = Minor eg superficial laceration
  - 2 = Moderate eg fractured sternum
  - 3 = Serious eg open fracture of humerus
  - 4 = Severe eg perforated trachea
  - 5 = Critical eg ruptured liver with tissue loss
  - 6 = Maximum eg total severance of aorta
  - 9 = Not specified

Head Injury Criteria

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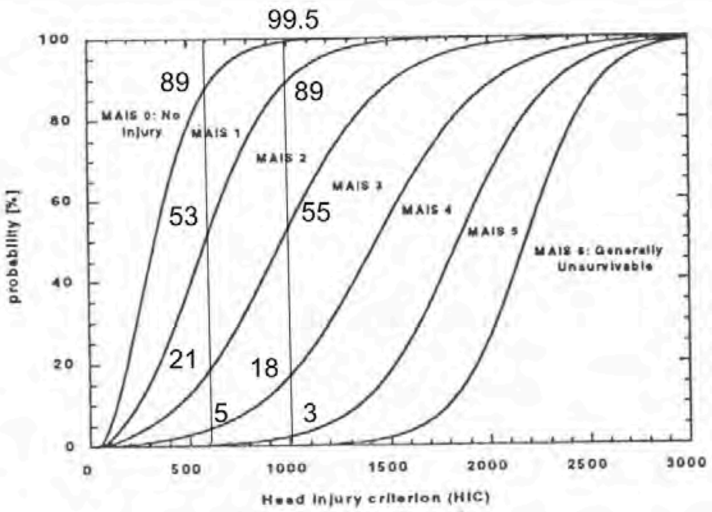

Prasad / Mertz Probability of a specific head injury

Principles of energy, impact and rebound

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- You may believe that a fall of a child onto a playground undersurfacing material is a simple matter when considering the forces involved
- Nothing could be farther from reality
- This simple fall produces a large number of forces and energy transfers
- When the child impacts upon the surfacing there is an equal and opposite force that impacts upon the child's body
- An energy wave enters the child's body and travels through the body at a variety of velocities and frequencies and is absorbed and attenuated by the bones, organs and soft tissue to varying degrees

Principles of energy, impact and rebound

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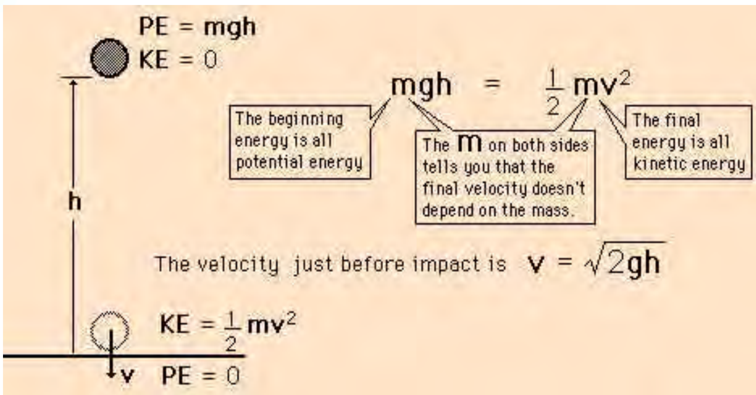

Sphere falling onto a playground IAS

Principles of energy, impact and rebound

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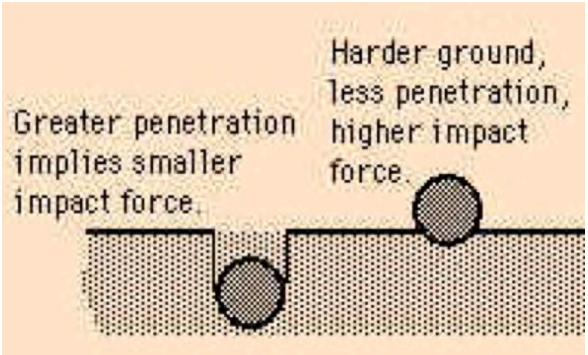

Sphere falling onto a playground IAS

Principles of energy, impact and rebound

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- ✔ In the playground no impact is perfectly elastic, all impacts are inelastic to some degree and there is always an accompanying irreversible flow of energy
- ✔ The IAS material exhibits hysteresis
- ✔ The kinetic energy is converted permanently to other forms of energy
- ✔ Work is done on the undersurfacing material during the impact and during this impacting process heat is generated (in rubber IAS) and dislocation (in loose fill IAS)
- ✔ Ideally we want all the kinetic energy to be absorbed by the IAS and not returned to the child

Principles of energy, impact and rebound

- ✓ The product of average force and the time over which the force is exerted is called the impulse of force

$$F = m \,.\, a = m \,.\, \Delta v / \Delta t$$

- ✓ The impulse of the force equals the change in momentum

$$Impulse = F \,.\, \Delta t = m \,.\, \Delta v$$

- ✓ Minimizing an impact force

$$Impulse = m \,.\, \Delta v = {}_{\text{Reduce impact}} \downarrow F_{average} \,.\, \Delta t \uparrow^{\text{Extend time}}$$

- ✓ Extending the time of the collision will decrease the impact force by the same factor

INCREASE THE TIME DURATION OVER WHICH THE IMPACT FORCE IS APPLIED

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How do we minimize the impact force?

- ✓ Alternatively, the same scenario can be examined with the aid of the work-energy principle

$$PE = KE = Work = {}_{\text{Reduce impact}} \downarrow F \,.\, d \uparrow^{\text{Extend penetration distance}}$$

- ✓ An impact that stops a moving object must do enough work to take away its kinetic energy, so extending the penetration distance during the impact reduces the impact force

INCREASE THE PENETRATION DISTANCE

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How do we minimize the impact force?

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- ✓ In addition to decreasing the HIC, the following characteristics are known to improve the performance of an IAS:

DECREASE THE RATE OF CHANGE OF VELOCITY wrt TIME (ie reduce g_{max})

DECREASE THE RATE OF CHANGE OF ACCELERATION wrt TIME (ie reduce j_{max})

DECREASE THE CHANGE IN MOMENTUM (ie reduce the bounce)

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Principles of energy, impact and rebound

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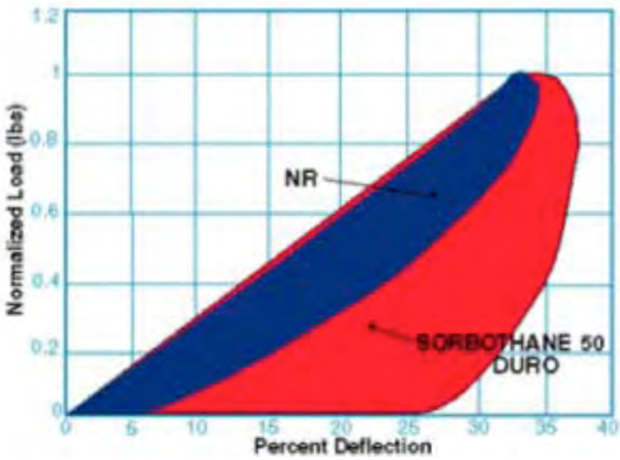

Sorbothane and natural rubber (force v displacement)

How do we minimize the impact force?

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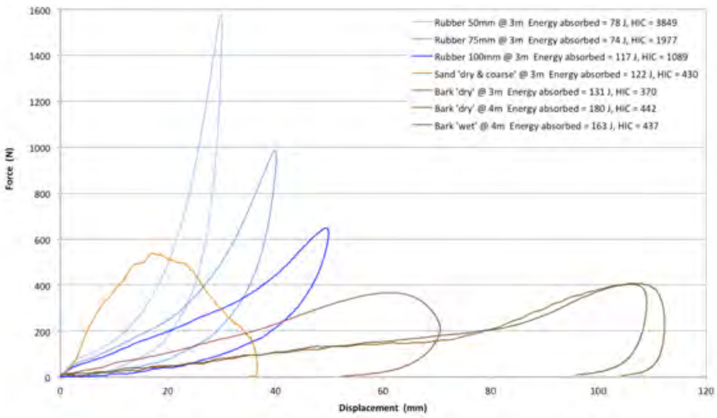
- ✓ Increase area under the Force v Displacement curve to remove more impact energy from the system



INCREASE THE HYSTERSIS

Threshold for hazards in Australia

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- ✓ **All Australian Standards use ISO 6489 Channel frequency class 1000, minimum sampling rate 8000 Hz**
- ✓ **The following is a chronological list of the Australian Standards that measure impact attenuation properties**
  - AS/NZS 4422:1996 Playground surfacing – Specifications, requirements and test method
  - AS 3533.4.1:2005 Adventure rides and devices - Land-borne inflatables devices
  - AS 4989:2006 Trampolines
  - AS 2316.1:2009 Artificial climbing structures and challenge courses – Fixed and mobile artificial climbing and abseiling walls
  - AS 3533.4.2:2013 Adventure Rides and devices - Contained Play Facilities
  - AS DR 4989:201x Trampolines

Threshold for hazards in Australia

AS/NZS 4422:1996 Playground surfacing – Specifications, requirements and test method

- 5.0 kg J-type headform
  - Rationale: This was the headform used in 1996 the Australian test labs to test motorcycle helmets.
- <1000 HIC, <200g
  - Rationale: Determine the critical fall height of the IAS within the adjacent fall zone. The Standard was based on prEN 1177 with local modifications. The maximum fall height is limited to 2.5 m by the maximum FHoF of the playground equipment (this will shortly increase to 3.0 m max when Australia adopts EN 1176:2004).
  - For unitary surfaces 4 drops in same location with at least 1 drop at a height above <1000 HIC or <200g with interpolation rounded down to closest 0.1 m.

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Threshold for hazards in Australia

AS 3533.4.1:2005 Adventure rides and devices - Land-borne inflatables devices

- 4.6 kg hemispherical or 5.0 kg J-type headforms
  - Rationale: The Standard does not disadvantage existing testing houses and encouraged an orderly transition to 4.6 kg hemispherical headform.
- <1000 HIC, <200g max at the equipment FHoF (700 mm max)
  - Rationale: The maximum FHoF for this class of play equipment is 700 mm and children are supervised so the potential risk exposure is moderated. The FHoF is deemed to be 700 mm even if the equipment is less than this height. Four drops in the same location to subject the sample to accelerated aging and test for longevity. The highest value is recorded.

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Threshold for hazards in Australia

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AS 4989:2006 Trampolines

4.6 kg hemispherical or 5.0 kg J-type headforms

Rationale: The Standard does not disadvantage existing testing houses and encouraged an orderly transition to 4.6 kg hemispherical headform.

200g max, impact duration > 6 ms at 1.5 m FHoF (deemed)

Rational: Testing house selects 'worst case' test locations. Four drops in the same location subjects the sample to accelerated aging. The impact duration replaced the HIC as a pass/fail criterion due to the poor reproducibility associated with multi-peaked acceleration pulses and large variation in HIC for drop to drop (ie 1200 HIC followed by a 300 HIC in the same location). The impact duration ($t_{end} - t_{start}$) was used since there was no HIC duration ($t_2 - t_1$). The 6 ms duration was used to force the manufacturers to use impact attenuating padding that brought the headform to rest over a longer duration, thus decreasing the 'thud' (instantaneous stop).

47 www.tuv.at

Threshold for hazards in Australia

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AS 2316.1:2009 Artificial climbing structures and challenge courses – Fixed and mobile artificial climbing and abseiling walls

4.6 kg hemispherical or 5.0 kg J-type headforms

Rationale: The Standard does not disadvantage existing testing houses and encouraged an orderly transition to 4.6 kg hemispherical headform.

1000 HIC, 200g max, impact duration > 3 ms belayed areas at 1.5 m FHoF (deemed)

Rationale: Climbers can fall from low heights even when they are being belayed so an IAS is required. As they climb higher the rope is taken in and the probability of a fall onto the ground is reduced. Time duration of the acceleration pulse is a third pass/fail criterion. When Australia went to public comment EN 1177 was still using the time duration (not HIC duration) to invalidate the impact event.

200 HIC, 40g max, impact duration > 12 ms non-belayed areas at the measured maximum FHoF (ie bouldering area)

Rationale: Climbers are not belayed and can fall awkwardly from any height. It was given that they could fall onto their coccyx or spine and the IAS needed to be appropriate for this risk exposure. An experimental study was conducted of all the bouldering areas within Sydney-based climbing gyms. The pass/fail thresholds of 40g and 12 ms adopted based on these experimental data (typically 400-500 mm thick bags stuffed with open-cell foam a 3.5 m FHoF = < 35g, < 120HIC, > 30 ms).

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Threshold for hazards in Australia

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AS 3533.4.2:2013 Adventure Rides and devices - Contained Play Facilities

- 4.6 kg hemispherical or 5.0 kg J-type headforms
  - Rationale: The Standard does not disadvantage existing testing houses and encouraged an orderly transition to 4.6 kg hemispherical headform.
- <1000 HIC, <200g max, HIC duration > 5 ms, jerk max < 40k g/s
  - Rationale: This was the first Australian Standard to use the rate of change of acceleration as a pass/fail criterion. Research by Stapp had confirmed that high jerk values were life threatening. Extensive research by UTS had confirmed that an IAS could pass the traditional 200g 1000HIC thresholds but still have extremely high jerk values and thus be hazardous to children falling. UTS also tested a variety of products that exhibited low jerk values for similar fall heights. Because such products existed we knew it was possible for synthetic IAS products to be manufactured or poured in-situ, which complied with this more onerous requirement.
  - The Standard uses HIC duration (not time duration) as EN 1177 adopted this in 2008.

Threshold for hazards in Australia

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AS 3533.4.2:2013 Adventure Rides and devices - Contained Play Facilities (cont.)

The Standard also increased the HIC duration pass/fail criteria from 3 ms to 5 ms. Increasing the time to bring the headform to rest during the most severe period of the impulse reduces the severity of impact. This 5 ms duration was set to mirror to 40k g/s threshold. Australia now had 4 pass/fail criteria that forced the acceleration pulse to conform to a tight window. This acted as a filter while still maintaining the original injury severity values of 1000 HIC and 200g.

The objective with the chosen thresholds was to set their magnitudes so that all four failed at the same height for a normalized sample. We chose the Regupol sample that CEN TC136/SC1 WG1 had previously used for the round robin laboratory test for this purpose.

Threshold for hazards in Australia

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AS DR 4989:201x Trampolines

4.6 kg hemispherical only

Rationale: This is the first Australia Standard to restrict the missile to the 4.6 kg hemispherical headform. All testing houses have been given adequate notice; no longer considered discriminatory to force them to use the hemispherical headform. It is anticipated that all future Australian Standards will adopt the 4.6 kg hemispherical headform where appropriate.

200g max, impact duration > 6 ms at 1.5 m FHoF (deemed)

Rational: This Standard introduced mandatory enclosures for trampolines. The users would thus be funneled in and out the entry/exit of the enclosure barrier. Ten drops at the same location subjects the sample to accelerated aging and tests for longevity. Over a period of 10 years it was noted that manufacturers were using 'packaging foam' which technically passed the four-drop test but did not last the life of the product. The padding system was an integral part of the safety system and it is reasonable to assume that the safety system still functions after 12 months. A more onerous test was required to filter poor quality 'packaging' foam padding systems and force manufacturers to use EVA and other cross-linked foams that retained some impact attenuating properties after several years of usage.

Conclusions

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- ✔ More than one IAS performance criterion is needed to adequately minimise the likelihood and severity of injury
- ✔ The following IAS performance criteria should be considered when testing and designing IAS:
  - Minimise HIC
  - Minimise g_{max}
  - Minimise j_{max} (rate of change of acceleration)
  - Minimise bounce (rebound)
  - Maximise work (area in the hysteresis loop)
  - Maximise penetration
  - Maximise the time over which the child comes to rest

Panel discussion

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- ✔ Is the HIC a good indicator of exposure to injury in playgrounds?
- ✔ Is the 1000 HIC tolerance level appropriate?

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Do playground surfacing standards reflect reality?

Test results and findings

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