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TESI

"Sustainable Design For Passive Safety of Sports Equipment"

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A te che hai

sempre

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A Mariangela

Abstract

This thesis project concerned passive safety and sustainable assessment of protective polymer-based foam devices, actually installed in Sports Area, and it aimed to investigate regulations, severity of injuries, material absorption properties and testing procedures, in order to propose a new approach. Thus, a focus on international Sports injury statistics it has been done and mostly frequent accident mechanisms, falls and head collisions, highlighted. It has been also possible, through a study on Biomechanical issues, to comprehend evaluation methods of concussion thresholds and brain trauma degree. From product design process point of view, Eco-design principles were studied in order to minimize consumptions and emissions in a product life-cycle vision and Robust Design methods were applied in order to maximize product performances through a proper evaluation of design parameters. Sports area standards, provided by international organizations, were compared in order to extract testing procedures and related technical requirements. Therefore, a flexible impact testing apparatus was designed and built in Sports Equipment and Technology department of Chemnitz University of Technology: by replacing the falling striker, in fact, it has been possible to comply with the American ASTM F1292, the European EN 1177 and EN 913 specifications, and then realize the so-called, in scientific literature, "Low-velocity" impact experiments. Afterwards, three experimental program phases were followed and a huge number of Polyethylene foam architectures were tested according to the previous American and European testing protocols. Due to lacks in EN 913 and EN 1177 specifications, a new testing method was proposed by considering friction influences in guidance system of the apparatus; by adopting an ergonomic missile; by a joint monitoring on the characteristic parameters during impact tests, that are acceleration peak, Head Injury Criterion (HIC) and critical fall height. Main goals achieved during this research could allow sports area technicians and responsible in making proper evaluation concerns the selection of several protective devices, and could improve the safety level of sports participants during their practice.

Summary

Appended Papers:

Paper A: G. Costabile, S. Schwanitz, S. Odenwald, A. Lanzotti, "Enhancing Impact Testing of Protective Polymer-based Foams According to EN 913 for Application in Sports Area.", Proceedings of ADM Workshop 2012, Capri, Italy, September 19th -21th,2012, 8 pp., ISBN Number: 88-902096-9-0

Paper B: G. Costabile, G. Amodeo, M. Martorelli, A. Lanzotti, S. Odenwald, S. Schwanitz, "Improving Passive Safety of Sports Equipment Through Experimental Testing of New Protection Devices.", International Conference on Graphics Engineering, Madrid, Spain, June 19th – 21th, 2013, 6 pp., submitted,2013.

Paper C: G. Costabile, G. Amodeo, M. Martorelli, A. Lanzotti, S. Odenwald, S. Schwanitz, "Toward a new Approach for Passive Safety Assessment of Gymnastic Equipment.", AMME International Scientific Conference on Achievements in Mechanical and Materials Engineering, Gliwiche-Krakow, Poland, June 23th – 26th, 2013, 8 pp., invited paper, 2013.

Additional Publications:

Journal publications

G. Costabile, S. Schwanitz, S. Odenwald, A. Lanzotti, "Enhancing Impact Testing of Protective Polymer-based Foams According to EN 913 for Application in Sports Area.", submitted to IJIDeM Journal, 2013

1. Introduction

This research project has been developed within a scientific cooperation between International Joint Lab *IDEAS* (Interactive Design and Simulation for Advances Engineering), Scientific Responsible Prof. Antonio Lanzotti, and the Department of "Sports Equipment and Technology "(*SGT*) of Chemnitz University of Technology, Scientific Responsible Prof. Stephan Odenwald. The research topic concerned passive safety and sustainable assessment of protective polymer-based foam devices diffusely installed in Sports area during educational, professional or leisure activities. Even though physical activities have been widely recommended to prevent diseases by Health Care Systems all over the world, potential accidents and related injuries have been focused on research efforts in order to a better understanding of collision dynamics and tolerable human body limits. Starting from injuries statistics in sports area, several International organizations for standardization have been produced standard procedures in order to provide testing protocols useful to characterize material and, more generally, products in term of safety efficiency in case of athletes impact or during a normal use of them. Biomechanical studies has pointed the human head collision as the most severe potential injury to prevent and they have provided models in order to evaluate human head trauma degrees. Sports area standards, although biomechanical indexes have been adopted, appeared to not provide an unequivocal assessment method to chose, within two materials, which one comply with effective human safety needs by fixing, i.e., a scale of potential injury degrees. Actually, technicians and sports area responsible are not being able to properly practice safety regulations and this work aimed to allow them how to improve testing procedures by introducing safety criterion developed within this research project. To this end, a special impact testing apparatus has been designed and built in *SGT* department of Chemnitz University of Technology and it has been capable to perform low-velocity impact tests on several material configurations made of polymer-based foams and provided by *D&S-Didattica e Sport-S.r.l.*, protective devices manufacturing leader in Italy. Impact attenuation properties of materials under study were investigated by means of biomechanical indexes application and by enforcing standard units technical requirements and testing procedures.

1.1. Thesis Framework

Within this paragraph, Author intended to give a general overview on the whole thesis framework toward a better comprehension of the followed research phases during the doctoral program and reported in following thesis chapters. In the second chapters, named “Background”, it has been reported injuries statistics in order to underline Safety requirements needs in sports area; Physical and Biomechanical approach were took into account referring dynamics of head impact and life threatening brain injury limits evaluation; mostly adopted international safety standards were analyzed in order to extract testing apparatus technical requirements and procedures; eco-design principles were studied in order to minimize consumptions and emissions in a product life-cycle vision. In chapter 3, named “Experimental Program”, it has been focused deeply on specimens characteristics, the impact testing apparatus manufacturing phase, impact testing procedures adopted an results achieved that have been also synthetically and scientifically shown in the bottom of the thesis. These latter papers also reflected three different experimental programs carried out in Chemnitz University of Technology laboratories in three different time periods: September-December 2011;April-December 2012;January 2013. Each chapter, mostly “Experimental program”, frequently cross-referred to “Papers” section were, due to a typical scientific dissertation, it hasn’t been possible to detail completely all of contents; on the other hand, further and new results have been shown in chapter 3 and not reported in papers section due to them unavailability at the papers submission deadlines.

Following paragraph are intended to introduce papers aims, methods and goals, as an overview.

1.1.1. Paper A

"Enhancing Impact Testing of Protective Polymer-based Foams According to EN 913 for Application in Sports Area."

This study was the first step of the consecutive experimental programs and started from a particular Sports area standard actually adopted as a testing protocol on shock absorption properties of gymnastic equipment, the EN 913. By means of integration of the previous standard units requirements with those established by the mostly referenced ASTM 1292, a special and flexible impact testing apparatus was designed and built; a pilot investigation on impact attenuation properties of two different protective devices it has been done; limitations of EN 913 procedure requirements were finally underlined through comparison between achieved results and others certified, on the same specimens, by an external accredited laboratory.

1.1.2. Paper B

"Improving Passive Safety of Sports Equipment Through Experimental Testing of New Protection Devices."

This paper and the related experimental program took into consideration know-how acquired with the previous testing experience and new methods and new monitored parameters allowed the group of research to define a new impact testing protocol capable to evaluate brain injury risks through *Head Injury Criterion* (HIC) calculations. A major number of material configurations were tested and special indexes were proposed from safety and sustainable design point of view.

1.1.3. Paper C:

"Toward a new Approach for Passive Safety Assessment of Gymnastic Equipment."

This is the most recent study developed in the same international laboratory were the impact testing apparatus was built and last two experimental sessions were performed. D&S Company provided a huge number of specimen configurations, manufactured by following design guide lines previously obtained through impact tests in papers A and B. New impact testing results were obtained by analyzing missile shape influences according different standards procedures. Results have confirmed again limitations of performance parameters and criterions adopted by international organizations for standardizations from athlete passive safety point of view and a special impact testing protocol were finally suggested by authors in a integrative way of requirements and goals reached during all of the impact testing periods.

2. Background

2.1 Sports Injuries Statistics

A recent study made by Steffen et Al. [1] has underlined both benefits and risks of potential injury related to sports participants physical activities. The physical activity guidelines of the American College of Sports Medicine recommend adults achieve 20-30 min of vigorous exercise at least 5 days a week for optimum functional capacity and health. Such a regular physical activity reduces the risk of premature mortality in general, and of coronary heart disease, hypertension, colon cancer, obesity, and diabetes diseases in particular. On the other hand, it is well described whether these health benefits outweigh the risk of potential injury and long-term disability associated with sports participation, especially at the elite level. Some injury types are of particular concern, either because they can be severe, such as head and knee injuries, or common, such as ankle sprain or hamstring strain injuries. Thus, to maximize the health benefits of sports and exercise and to minimize the direct and indirect costs associated with injury, developing methods to prevent sports injuries is a necessary goal. In injury characteristic and mechanism sections of the paper , head and impact were identified as the mostly frequent body part treated to hospitalization and manner to concuss, respectively, during activities in several Sports fields. Head and neck injuries are common across many sports. Horse riding, ice hockey, skiing/snowboarding, soccer and other football codes (e.g. American and Australian football) are sports where head injuries can result from a fall or from direct contact with sports equipment or other athletes. In paper dissertation, it has been clearly pointed that a head injury is the most frequent reason for hospital admission and the most common, although serious head injuries are rare. The majority (90%) of head injuries are minor, defined as mild concussions. The latter typically result in rapid but short-lived impairment of neurological function that resolves spontaneously. Although most athletes with head injuries recover uneventfully following a single concussive episode, repetitive mild head trauma may cause cognitive impairment. Authors paid also attention on incurred costs by Healthy Care Systems and prevention strategies to reduce these risks.

A statistical report [2] on sport injuries in the European Union agreed with the first previous study. Annually, almost 6 million persons needed hospital treatment due to accidents related to Sports activities, of whom 10% require hospitalization for one or more days. Based on the Eurostat and WHO mortality databases the number of sports fatalities can be estimated at 7000 per year: in Fig. 2-1 a brief scenario on deaths, disabilities, hospital admissions and hospital treatments is shown.

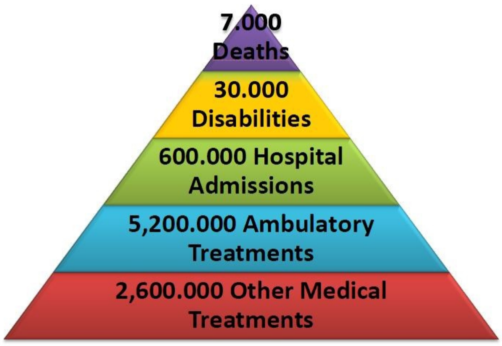
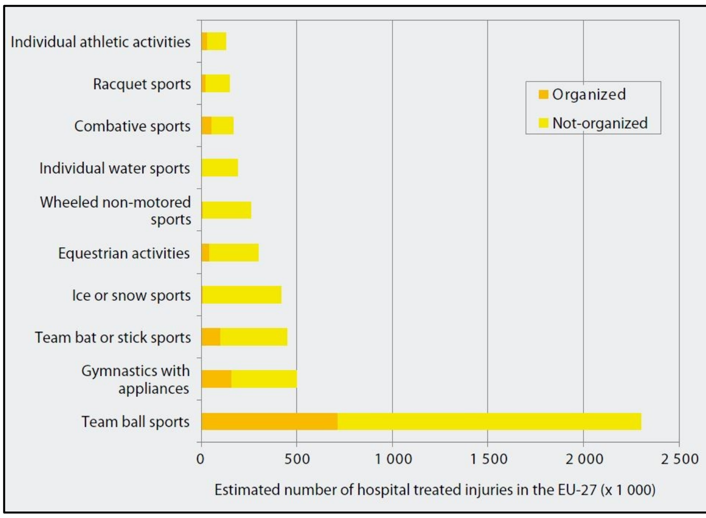


Fig. 2-1 Source: Eurostat 2005-2007; EU IDB 2005-2007 for the European Union (EU27)

The fatal accidents in sport may relate to various categories of sport, like rock climbing, boating sport, horse riding, drowning in natural bodies of water and swimming pools and non-traffic bicycle accidents. As to the non-fatal injuries related to physical activities and sport, each year about 4.5 million people aged 15 years and above are being treated in hospital for a sport injury. 25% of the sport injuries affect young people in the age of 15 to 24 years. When children under the age of 15 are included, the estimate is 5.8 million sport injuries annually. “Team ball sport” account for about 40% of all hospital treated sport injuries. By specific type of ball sport the ranking order in team ball sport is: soccer (74%), basketball (8%), volleyball

(7%), handball (3%). In Fig. 2-2, all of these last shares are shown with an additional insert that ranks the main type of sports by their share of head injuries.



Type of sports	Share of head injuries (of all injuries in this type of sports)
Ice-Hockey	28%
Squash	28%
Swimming	25%
Boxing	21%
Ice skating/dancing	19%
Cycling	16%
Soccer	13%
Horseback riding	13%
Skiing	11%
Basketball	10%
Skateboarding	10%

Fig. 2-2 EU-27 estimetes of hospital treated sports injuries by type of sports, participation and share of head injuries

The knowledge of the specific injury patterns for each type of sport is important to know in order to adequately address the issue of personal protection equipment in sports. Share of head injuries underlined the need to protect this human body part in case of crash and it is possible to comprise various types of injuries, from cuts which are quite frequent in squash to brain damage due to lack of oxygen, which is common in near-drowning. Sport helmet protect in particular from traumatic brain injuries due to severe blows. While helmets are well established e.g. in ice-hockey, cycling and horseback-riding, they are much less accepted in squash, and unknown in soccer, basketball or volleyball. The various characteristics of the sports lead to different distributions of accident mechanisms (Fig. 2-3). Direct bodily contact with other players have not unexpected the highest shares in rugby (and American football) and football. Falling and stumbling play an important role in all team ball sports, whereas the typical one-to-one situation causes many falls, although in many cases without direct bodily contact with an opponent. The most severe injuries are definitively related to the head and arise mainly (30%) due to impacts (falling, stumbling) with the ground/surface, equipments or opposite players.

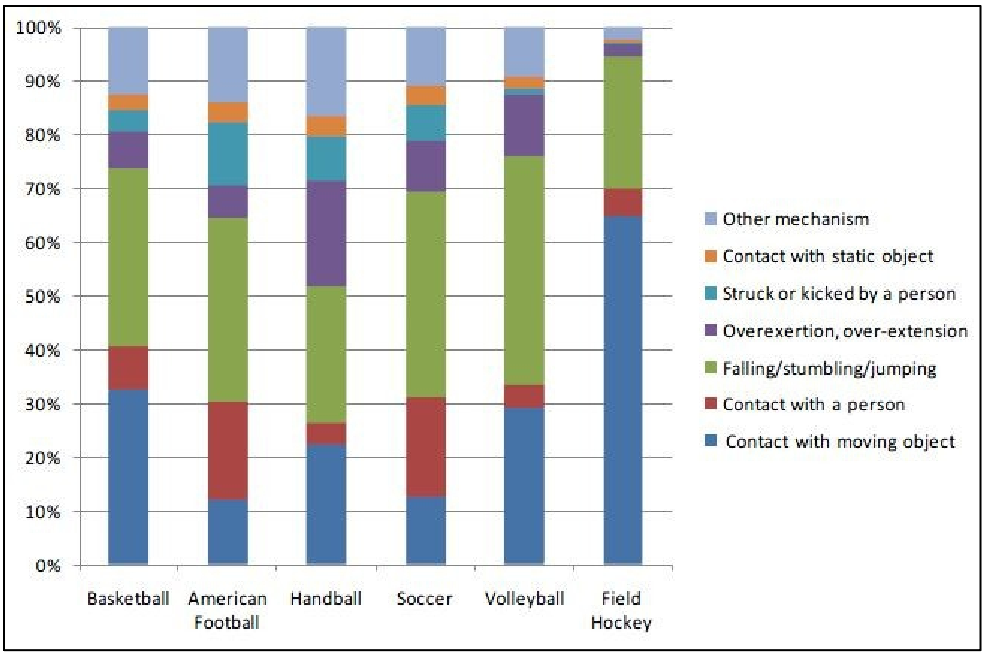


Fig. 2-3 Accident mechanism in selected team-ball-sports

In injury cost analysis, direct costs comprises both costs related to the injury (e.g. medical treatment) as well as to the event (e.g. material damage). Indirect (socioeconomic) costs are other economic losses, mainly the loss of productivity due to sick-leaves, impairments, and years of live lost. For sport injuries, there are no comprehensive and comparable estimates available at EU-level. In practice only the number of days of in-hospital treatments is available as cost indicator. The EuroCost study performed the latest cost calculation analysis for countries in the EU, that could provide more detailed cost information related to a selection of sport categories. In Tab. 2-1 an example of Eurocost methodology is given for team-ball-sports mentioned above.

Type of sport	Days	ED	Total	
Soccer	127.256.426	161.574.236	288.830.662	70%
Basketball	9.575.161	17.884.000	27.459.160	7%
Handball	4.592.688	14.343.170	18.935.858	5%
Volleyball	17.964.018	14.185.800	32.149.818	8%
American Football	6.863.611	6.463.419	13.327.030	3%
Field Hockey	9.761.580	19.946.673	29.708.253	7%
Total	176.013.482	234.397.298	410.410.780	100%
of all sports			25%	

Tab. 2-1 The medical cost of high risk team sports in the European Union

A special study [3] conducted by the U.S. Consumer Product Safety Commission (CPSC) to address an inquiry from ASTM International on playground equipment-related injury and death scenarios involving children under the age of 2. The injury data is based on a study of playground-related injuries treated in U.S. hospital emergency rooms from October 2000 to September 2001. Playground-related fatalities reported to CPSC from January 1990 to August 2002 were also reviewed. During the special study period, there were an estimated 8,250 children (under the age of 2) treated in U.S. hospital emergency rooms for injuries associated with playground equipment. Lacerations, contusions and abrasions were the most commonly reported injuries (52 percent). Seventy-eight percent of those relatively minor injuries were to the head or facial region. Fractures, sprains and strains were the second most often reported injuries, accounting for 30 percent of the total. The head and facial region of the body was involved in 53 percent of all the injuries. Nineteen percent of the head/facial injuries were of a more severe nature such as fractures, concussions or internal injuries. Forty-one percent (3,390) of the estimated injuries involved public playground equipment and 33 percent (2,730) involved home use equipment. The most common injury scenario was a fall, accounting for 50 percent of the total injuries. The lowest height from which a child fell in the study sample group was 1 inch and the maximum height was 10 feet. The second most common injury scenario was impact (colliding with or being struck by playground equipment) with 22 percent of the injuries. Protective surfacing on playgrounds is recommended for reducing the risk of serious head injuries. In this study the most common type of protective surfacing was wood chips, associated with 12 percent of the injuries. The most prevalent surfacing overall was grass (a non-protective surface), which was associated with 17 percent of the injuries.

Similar studies [4],[5] on playground equipment injuries has confirmed mortality and hospitalizations frequency showed above for sports participants, all over the ages, referring to elite and leisure activities, within public and house-use. These researches also underlined how inadequate surfacing, poor equipment design and lack of maintenance contributes to a major probability of concussion. On the other hand, although considerable effort has been devoted in recent years to the study, development and promotion of surfaces with appropriate shock attenuation properties it is expected. International organizations for standardization have been developed impact testing procedure based on mostly common used loose-fill materials like sand, wood chips, rubber. Unitary surfaces with viscoelastic properties appeared to be not took into adequate consideration due to a lack of experimental efforts and results.

This thesis project aimed to contribute to a definition of an exhaustive impact testing protocol by introducing polymer-based foam in protective surfacing materials and in order to appreciate them shock absorption properties comparing to those one normally used in public playground area.

2.2 Head Collision: Physics and Biomechanics

Previous statistics have shown that injuries to the head are responsible for a huge amount of death and hospitalization in all over the world and in many sport fields. A complete and scienfically analysis of potential head injuries in case of human crash has to start from anatomy of the complex system that is the human head.

The human head consists of three components (also shown in Fig. 2-4):

- The body skull – Cranial and Facial bones
- The skin and other soft tissue covering the skull- which consists of layers known as the SCALP (skin, connective tissue, aponeurosis, loose connective tissue and periostreum)
- The contents of the Skull- most notably the brain, but also including the brain's protective membranes (meninges) and numerous blood vessels

Injuries to the skin may be categorized as superficial or deep, and include contusion, laceration and abrasion. Injuries to the skull may break or more of the bones of the skull in which case the skull is said to have been fractured (broken). Injuries to the Brain and associated soft tissue are the results of either head impact or abrupt head movement (e.g. deceleration injury) or some combination of the two. Injuries may be due to the interior of the skull fracturing and being pushed inward (a depressed fracture), or from the brain impacting the interior of the skull, or from internal stressing of the brain (e.g. shear, tension, compression). The complexity of the head and brain system are reflected in the rather bewildering array of the head injury consequences. Three various methods are used to categorize brain injuries:

1. The cause of the injury, either contact vs non-contact
2. The type of injury, either primary vs secondary
3. The type of injury, either focal vs diffuse

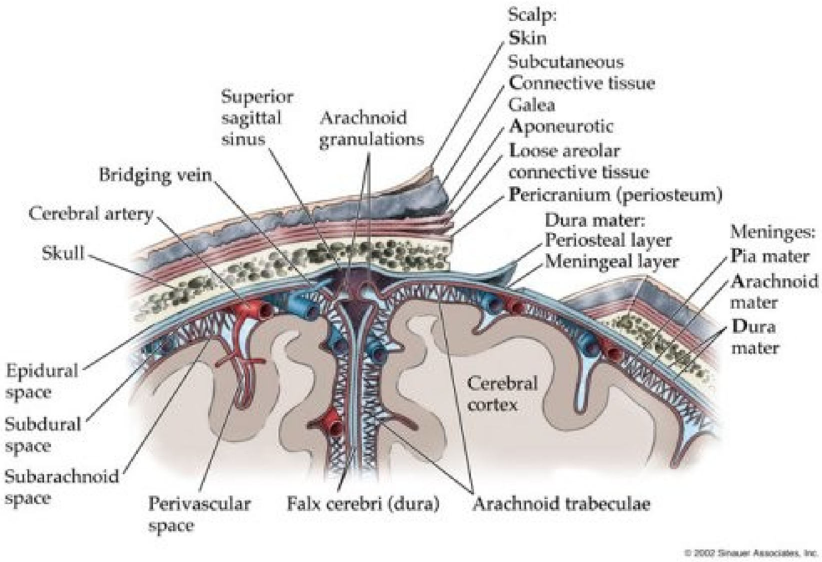


Fig. 2-4 The scalp, skull, meninges and brain [6]

Many authors [7]-[8] agreed with the diffuse axonal injury as one of the most common types of severe brain damage observed in closed head injury. It is thought to be associated with the progressive biomechanical tearing over time of axons in the cerebral hemispheres following a severe head impact. Loss of consciousness and brain swelling followed by loss of life or severe mental and motor deficits are common in this type of brain injury. Close head injury are, in great majotity of cases, a consequence of an impact to the head. However, there are references in the literature to the production of diffuse axonal injury in 'non-impact' experiments in which the head of an animal was accelerated in a manner that minimized the direct contact effects of an impact to the head. There are also reports of brain injury resulting from acceleration of the upper torso of an animal without any direct impact to the head. It is useful to underline the distinction between an impact to the head and an impulse transmitted to the head through the neck. Both an impact and an impulse can accelerate a stationary head (or decelerate a moving one) but an impact will also produce contact effects on the head, such as skull deformation or fracture, with an associated risk of injury to the brain. However, in practice it appears that injury to the human brain is almost always the result of an impact to the head, or to a protective helmet, rather than an impulse transmitted through the neck. An impact to a given location on the head can be characterized by the impact velocity and the physical properties of the struck or striking object. Finally an exhaustive analysis of the dynamic of impact it is needed in order to assess and evaluate transmission of the stresses to the head and severity of the collision.

2.2.1 Physics

According to Ibrahim et Al., falls are the most common environmental setting for closed head injuries treated in pediatric observational units and are responsible for 135 in every 100.000 deaths in children 15-17 months of age. Those clinical studies (and others referred to anthropomorphic test dummies used with the goal of understanding the kinematics of impact events) suggested that major contribution to injury severity it is related to fall height and impact surfaces. Cory et Al. specified that many factors have to be considered when investigating infant injuries possibly sustained from falls. These parameter will affect the severity and type of injuries sustained during a fall and include acceleration due to gravity, height of the fall, impact velocity, impact force, impact surface.

The acceleration (a) of a free fall is constant due to gravity ($g=9.806\ m/s^2$) and linear, that is in a straight line from the initial fall position towards the point of impact (Fig. 2-5). Acceleration is defined as the rate of change of velocity with respect to time. The velocity is the speed of a body in a given direction. Assuming linear acceleration and ignoring air resistance, the velocity at impact is directly related to the fall height by Newton's equation of motion:

$$v^2 = 2gs \qquad (1)$$

Where v is the final velocity, initial velocity equal to zero is assumed, g is the acceleration due to gravity and s is the distance (fall height).

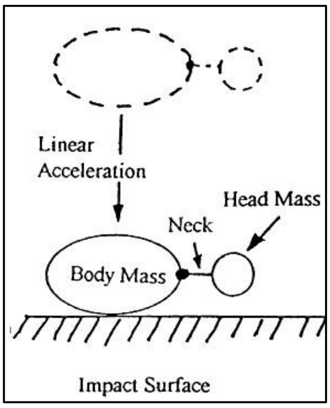


Fig. 2-5 Linear acceleration [10]

The impact surface influences many factor such as absorption of kinetic energy, acceleration on impact, impact duration, impact force and area of contact. These last two factors determine stress (force/unit area). A body acquires kinetic energy (KE) as it falling. Almost of the energy is transferred to and absorbed by the impact surface. The degree to which an impact surface deforms affects how much KE is absorbed by the surface and thus the amount that remains to the be absorbed by the body. The relationship between KE, velocity, force and mass of the impact body and the stopping distance (or deformation distance) is given by following equation proposed by Newman [11] and illustrated in Fig. 2-6

$$Fd = \frac{1}{2}mv^2 = KE \quad \text{and} \quad F = \frac{KE}{d} \qquad (2)$$

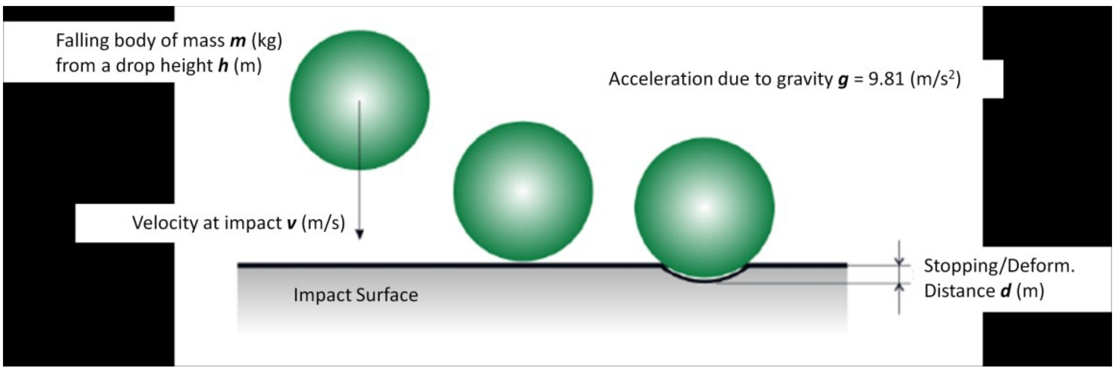


Fig. 2-6 Symbols adopted in equation 2

Where *F* (N) the average force during the impact. A greater stopping/deformation distance reduces force generated on impact and reduced force causes less damage to the impacting body. King et Al.[12] showed how, in term of g, the acceleration of the falling body on impact can be expressed as a ratio of the fall height *h* to the deformation distance *s*:

$$a = \left(\frac{h}{s}\right)g \qquad (3)$$

This equation can also illustrate how a greater deformation distance reduces impact force. If, during an impact event, a surface deforms (alters in shape) energy is absorbed by the work done to deform the material. If a surface is curved or irregular, deformation may increase the impact/contact area between the body and the surface and dissipate the force over a larger area, therefore reducing the force per unit area (stress) on the body and thus, the severity of injury. This situation is well illustrated in Fig. 2-7 where in case of impact on soft surfaces, the large contact of the body at impact decrease force per unit area, a large amount of deformation occurs and the KE is absorbed by the material. On the contrary, referring to hard surfaces, the KE is absorbed by the object at the impact (head) due to a small amount of deformation and a small contact on the surface that increase the force per unit area (stress).

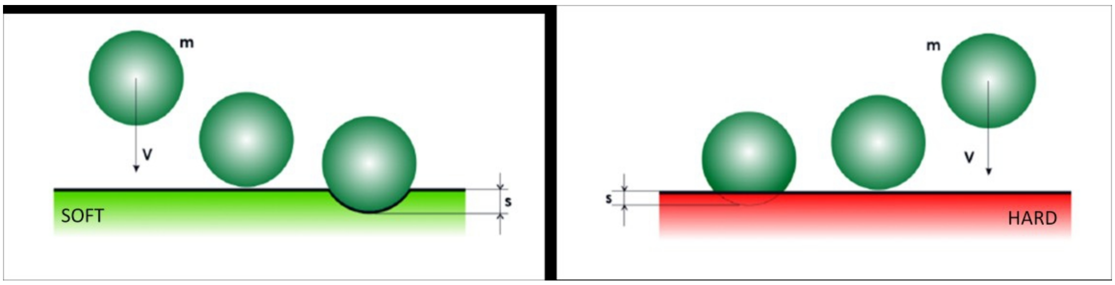


Fig. 2-7 Body at impact on soft and hard surfaces

Snyder [13] suggested that an increase in impact duration reduced injury, in particular, “the resilient qualities of these impacted materials, which deformed over relatively long time period, were evidently quite effective in decelerating the body with minimal, or no injury, in these cases”, and according following equation:

$$t = \sqrt{\frac{2s}{a}} \qquad (4)$$

Where *t* is the impact duration (s), *s* the deformation distance (m), and *a* the acceleration (m/s^2).

2.2.2 Biomechanics

There are many variables which may cause injury during impact: the kinetic energy of the body, the force imparted to the body, the stress and strain of the bones and tissues, and the overall acceleration of the body. For every fall a different proportion of each of these factors is responsible for the injuries. Gadd, in 1966, suggested that although the body is exposed to these other variables under impact, "it has been impractical except in very limited instances to obtain transducer readings which are directly associated with the injury, and, as a results, the overall head acceleration, a rather indirect measure, has come into wide use". This measure is used to test products such as safety helmets, the inner structure of cars and playground surfacing. A significant study on methods for assessment of head injury potential was done by Cory et Al. 45, where all of the mechanisms are categorized in Head Injury Models (HIM).

The first of HIM is the *peak-g method*, and it utilizes the maximum recorded acceleration during an impact event and can provide simple information with regard to the ability of a surface to absorb the energy of impact. For a given fall height, a high peak g suggests that the surface provides little cushioning on impact, i.e. the object slows down over a short time period. A relatively low peak g suggests the surface cushions the impact, i.e. the object slows down over a longer time period and the surface absorbs a greater proportion of the impact energy. Such a situation is shown in Fig. 2-8 where the red waveform represents bad cushioning properties due to a relatively high peak on a short period of time. On the other hand, the green waveform seems to absorb better the impact energy due a distribution of the shock on a longer period of time. The peak g is lower than the previous one. It's important to underline that this method indirectly takes into account impact time: it is defined within a measurement of the peak g acceleration, but the duration of the impact pulse is not considered and directly measured.

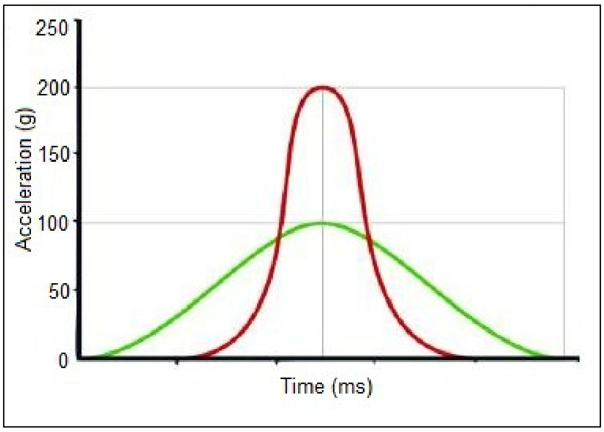


Fig. 2-8 Acceleration-Time trace

A study of the current literature reveals a division of opinion concerning the peak g measure a child could be subjected to without sustaining a serious head injury. Many authors has pointed different peak acceleration threshold before injuries occur and it seems that all of these biomechanic efforts go into the direction of 200 g value as a life threatening threshold. Others agree that the maximum acceptable level of impact that humans could sustain is referred to the value of 50 g. And this is can be seen on the *Wayne State Tolerance Curve* (WSTC) (the second of the HIM), an experimental work done by Lissner et Al. [14] at the Wayne State University in Michigan involving drop tests of four human cadavers with measurement, and comparison, of acceleration, intracranial pressure and structural damage. The WSTC demonstrated that the severity of head injury was dependent both on the magnitude and the duration of the impact. Values above the curve suggest a danger to life and values below are tolerable. For example, from the WSTC shown in Fig. 2-9 it can be seen that an impact force of 100g for 6ms represents the same threshold of injury as 200g for 3 ms as they both lie on the curve. However, an impact force of 75 g for 10 ms would represent danger to life but 150 g for 3 ms would be acceptable. The WSTC has been criticized on various grounds since its inception: the limited number of data points, possible questionable instrumentation techniques, a lack of documentation regarding the scaling of animal data used in its extension to longer duration, and the uncertainty of definition of the acceleration level. From a biomechanical standpoint the main criticism of the WSTC is that there have been no direct demonstrations of functional brain damage in an experiment in which biomechanical parameter sufficient to determine a failure mechanism in the tissue were measured.

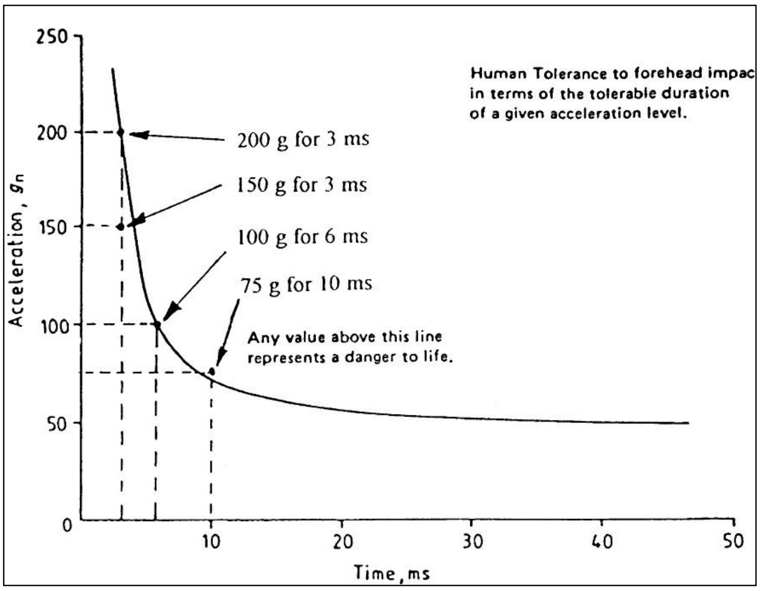


Fig. 2-9 Human tolerance to for head impact in terms of the tolerable duration of a given acceleration level

Gadd [15] developed the *Gadd Severity Index* (GSI) (the third of HIM) to fit the WSTC curve, with a value greater than 1000 considered to be dangerous to life (equation 5). It was based not only on the original Gurdjian (1963) data, but also upon additional long pulse duration data by means of the Eiband (1959) tolerance data and other primate sled tests. The GSI provided a good fit for both the short duration skull fracture data and the longer duration Eiband data out to 100 msec duration.

$$GSI=\int_0^t a^n dt < 1000 \qquad (5)$$

Where *GSI* is the function of acceleration and time of impact, *n* the weighting factor based on previous experimental data, *a* the acceleration on impact (in units of gravity, g), *dt* the duration of acceleration on impact (s), and *1000* is the threshold of danger to life for internal head injury during frontal blows. The GSI is calculated by integrating the whole acceleration waveform, therefore, a relatively long duration, low acceleration impact, could give the same GSI value as a short duration, high acceleration impact. In order to solve this problem, Versace [16] first proposed an alternative interpretation of the WSTC combined with information derived from experiments conducted on crash dummies. The method was known as *Head Injury Criterion* (HIC) (the fourth of HIM) and addressed the shortcomings of the GSI, providing comparable head injury tolerance values irrespective of the acceleration waveform shape. The HIC considers the more injurious portion of the impact waveform, the peak and close to peak sections, and excludes the less injurious sections therefore giving a more accurate head injury tolerance level. It is defined according the following equation:

$$\mathrm{HIC}=\max_{(t1,t2)}\left\{\left(t_2\text{-}t_1\right)\left(\frac{1}{t2\text{-}t1}\int_{t1}^{t2} a\,dt\right)^{2.5}\right\}<1000 \quad (6)$$

Where $(t_2\text{-}t_1)$ is the portion of the waveform to be measured during which HIC attains a maximum value, *a* the acceleration on impact (in units of gravity, g) and *dt* the duration of the acceleration on impact (s).

Prasad and Mertz [17] analyzed available test data from human surrogates to determine the relationship between HIC and injuries to the skull and brain. Methodologies used to analyze the brain injury data had a number of limitations, and resulted in a risk curve nearly identical to the skull fracture injury risk. Skull fracture data consisted of head drop tests on both rigid and padded flat surfaces, sled tests against windshields, and helmeted drop tests. The combined set of data consisted of 54 head impacts, with HIC values ranging from 175 to 3400. HIC durations ranged from 0.9 to 10.1 msec. The lowest HIC value associated with a skull fracture was 450, and the highest HIC value associated with a non-fracture was 2351. These data were analyzed by Hertz [18] fitting normal, log normal, and two-parameter Weibull cumulative distributions to the data set, using the Maximum Likelihood method to achieve the best fit for each function. The best fit of the data was achieved with the log normal curve, shown in Fig. 2-10 where is shown the plot of probability of skull fracture (AIS≥2) [19] to HIC (at 36 ms) values.

$$\mathrm{P(fracture,\ AIS}\geq 2)=\mathrm{N}\left(\frac{\ln(\mathrm{HIC})\text{-}\mu}{\sigma}\right) \quad (7)$$

Where N is the cumulative normal distribution, μ=6.96352 and σ=0.84664

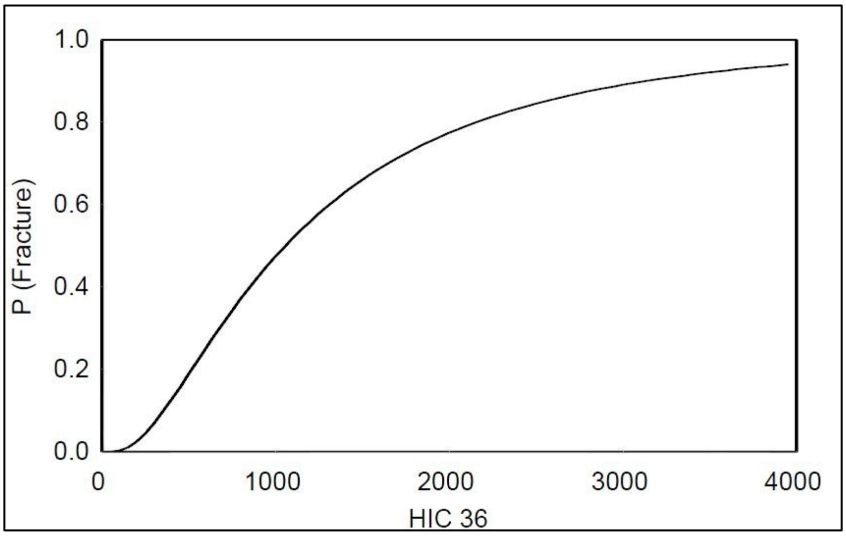


Fig. 2-10 Injury risk curve for the Head Injury criterion (HIC)

In correspondence of an HIC value of 1000 there is a 47% probability (risk) of skull fracture (AIS≥2) for a middle-size male adult or, alternatively, a 16% risk of life threatening brain injury (fatal injury, AIS≥5). Those threshold were established both on Prasad and Mertz study (only the AIS≥4 were developed by Prasad and Mertz) and on Expanded Prasad/Mertz curves by National Highway Traffic Safety Administration [20], as following:

$$\begin{aligned}
AIS1 &= \left[1+\exp\left((1.54)+\frac{200}{HIC}\right)-0.0065*HIC\right]^{-1} \\
AIS2 &= \left[1+\exp\left((2.49)+\frac{200}{HIC}\right)-0.00483*HIC\right]^{-1} \\
AIS3 &= \left[1+\exp\left((3.39)+\frac{200}{HIC}\right)-0.00372*HIC\right]^{-1} \\
AIS4 &= \left[1+\exp\left((4.9)+\frac{200}{HIC}\right)-0.00351*HIC\right]^{-1} \\
AIS5 &= \left[1+\exp\left((7.82)+\frac{200}{HIC}\right)-0.00429*HIC\right]^{-1} \\
AIS6 &= \left[1+\exp\left((12.24)+\frac{200}{HIC}\right)-0.00565*HIC\right]^{-1}
\end{aligned} \quad (8)$$

2.3 International Sport Safety Standards

Sports activities 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 facilities (ie. walls) or striking the surface during a fall can all result in brain trauma. Also, in many sporting contexts (Sports Area in Fig. 2-11), 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, as the biomechanics section of the thesis as shown. Starting from this scenario, International Organizations for Standardization have been studied and developed sport materials testing procedures in order to assess athletes risks related to falls, entrapments and others way and provide regulations and material requirements to protect participants during sport activities.

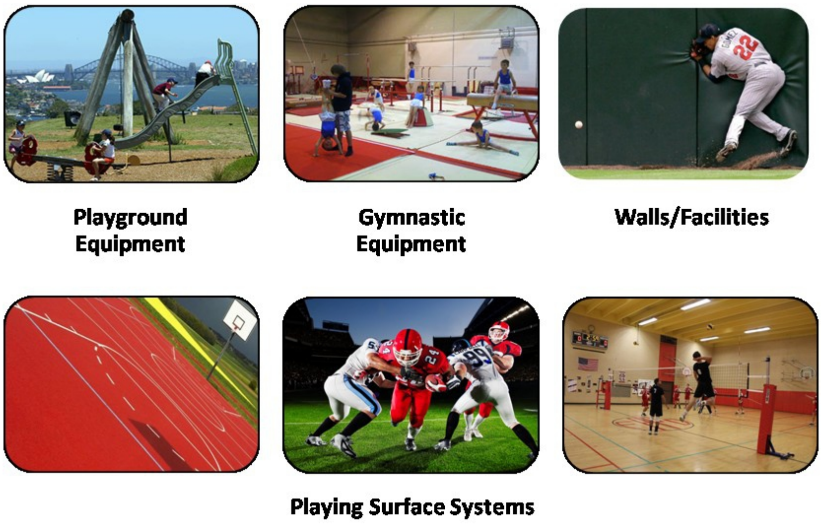


Fig. 2-11 Sports Area

Several studies on sports area injuries [3],[4],[5] conducted by the US Consumer Product Safety Commission (CPSC) on request of the American Society for Testing and Materials (ASTM), on accidents related to Public or Home playground equipment has established a difference between protective or non-protective surfacing materials, depending on the registered number of death/hospitalization and related to different surfacing materials. It has been shown, in fact, that different surfaces present different risks of head injury. For example, it has to be considered as protective those materials that are typically used in playground surfacing include *organic loose fills*, (e.g. wood chips, bark dust, engineered wood fiber),*inorganic loose fills* (e.g. gravel, sand, crushed marble), *manufactured products* (poured in place rubber/urethane compounds, rubber tiles, etc.) and *unitary surfaces* (i.e., extruded polymer-based foams or other plastics). Non-protective materials has to be considered those ones that don't offer cushion properties under an impact loading (i.e., concrete, asphalt). The latter researches show 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. International Organization for Standardization (i.e. ASTM in America or CEN in Europe) were in an effort to provide a safe and attainable degree of impact attenuation by developing standard procedures on sports area protective surfacing evaluation. The primary goal of the surface shock attenuation standard was to prevent life threatening head injuries, although shock attenuating surfaces also appear to reduce the risk of other, non-fatal injuries. Fractures, lacerations and abrasions are more common, but the potential consequences of head injury are more severe.

The shock attenuation specification is based on an impact test that 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 through a typical low-velocity ([21],[22],[23]) impact testing apparatus (shown in Fig. 2-12) where an accelerometer-instrumented missile (differently head-shaped) is dropped on to the surface (specimen) from a measured height through a guidance system. Performance Parameters in term of the impact shock peak (is the peak "Gmax" reached by the acceleration-time trace during the impact of the missile on the specimen, Fig. 2-13) and Head Injury Criterion value (HIC - integral of a(t) that considers both the magnitude and the duration of the impact shock) are evaluated through a data recording system linked to the apparatus. Also the velocity at onset of the impact and the period of time within the impact event, are measured.

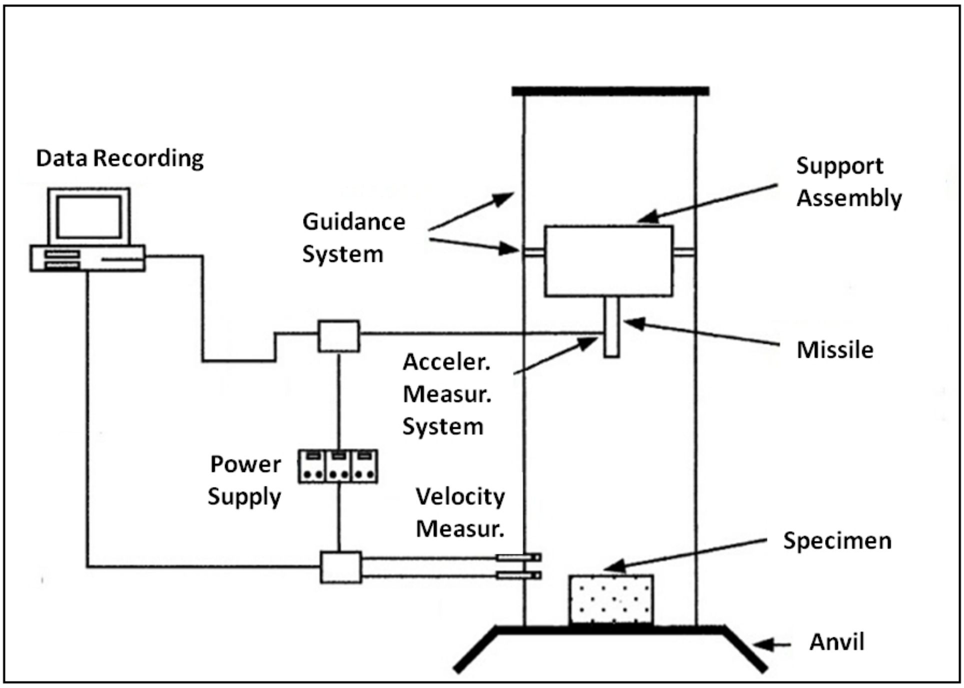


Fig. 2-12 Low-velocity Impact Testing Apparatus

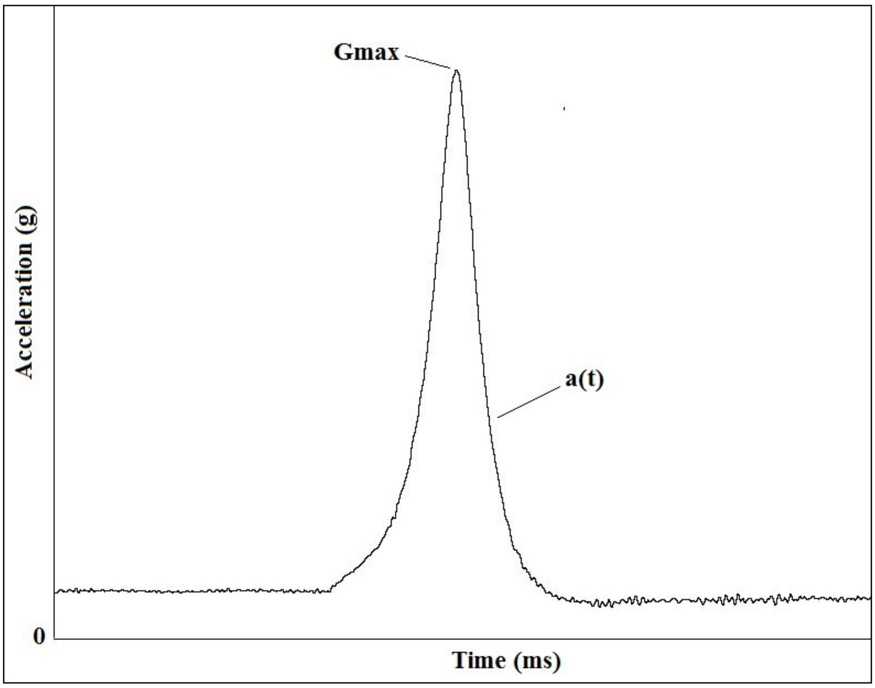


Fig. 2-13 Acceleration-Time trace

In order for an impact test to be useful in assessing the potential risk of head injury, the tolerance of the brain to impact loads must be documented so that the relationship between impact dynamics and injury risk can be quantified. To this end, several Performance Criterion were adopted in Standards procedures and, following, a brief review on the main International impact testing protocols is shown.

2.3.1 ASTM F1292 [24]

"Standard Specification for Impact Attenuation of Surfacing Materials Within the Use Zone of Playground Equipment"

- Application field: Playground Equipment
- Scope: This specification establishes minimum performance requirements for the impact attenuation of playground surfacing materials installed within the use zone of playground equipment.
- Surface Performance Parameters: The average g-max and average Head Injury Criterion (HIC) scores calculated from the last two of a series of three impact tests shall be used as measures of surface performance.
- Performance Criterion: The performance criterion used to determine conformance with the requirements of this specification shall be: a g-max score not exceeding 200 g and a HIC score not exceeding 1000.
- Summary of Test Method: *Critical Fall Height Test* - The impact attenuation of a playground surface or surfacing materials is measured using an impact test in which a missile is dropped onto the playground surface from a predetermined drop height. The acceleration of the missile during the impact is measured using an accelerometer and associated data recording equipment. The acceleration time history is analyzed to determine g-max and HIC scores. For each playground surface sample at each reference temperature and drop height, scores from the second and third of three consecutive drops are averaged to give average scores, with an interval between impacts of 1.5±0.5 min. The critical fall height of surfacing materials is determined by impact testing representative samples at a range of drop heights. The surfacing material is tested at temperatures of 25, 72, and 120°F (-6, 23, and 49°C). The critical fall height is determined as the highest theoretical drop height from which the surface performance parameters meet the performance criterion. *Theoretical drop height* shall be calculated from a measurement of impact velocity, v, using the formula $h = v^2/2g$, where g is the acceleration due to gravity.

- Impact Test System: *Missile* - The body of the missile shall be made of Aluminum Alloy 6061-T6, finished with a surface roughness of 1000 µin. (25 µm). The missile shall have a hemispherical impacting surface with an external diameter of 6.3 ± 0.1 in. (160 ± 2mm) (Fig. 2-14). *Supporting Assembly* - (for example, a handle or ball arm) may be rigidly attached to the missile as a means of connecting it to an external guidance system. The total mass of the drop assembly, which is the combined mass of the missile, accelerometer, and supporting assembly shall be 10.1 ± 0.05 lb (4.6 ± 0.02 kg). The mass of the supporting assembly alone shall not exceed 3.0 lb (1.4 kg). *Guidance Mechanism for Guided Impact Tests* – For guided impact tests; the missile may be connected to low-friction guides (such as monorail, dual rails, or guide wires) using a follower or other mechanism in order to constrain the fall trajectory of the missile to a vertically downward path. The guidance mechanism shall be constructed in a manner that does not impede the trajectory of the missile during its fall or during its contact with the surface being tested; other than necessary impedance caused by friction in the guidance mechanism. *Drop Height Control Mechanism* - The guidance mechanism or the support structure shall incorporate a means of repeatably positioning the missile at a predetermined drop height. *Release Mechanism* - A manual or electronically operated quick-release mechanism shall be provided as a means of initiating a drop of the missile. The operation of the release mechanism shall not influence the fall trajectory of the missile following release. *Acceleration Measurement System* - A transducers and associated equipment for measuring and recording the acceleration of the missile during an impact with an accuracy of within ±1 % of the true value. *Drop Height Measurement System* - A means of repeatably determining the missile's drop height with a resolution of 1 in(25 mm) and to an accuracy of ±1 % of the true value is required. *Velocity Measuring System* - A light gate device to measure the time an opaque flag interrupts a light sensor or other appropriate means. Velocity measuring device shall not interfere with or impede the trajectory of the missile and shall be capable of recording impact velocity with a resolution of 0.1 ft s^{-1}(0.03 m s^{-1}) and an accuracy of ±1 % of the true value.

- Unitary Surfaces: At least nine specimens of a specific unitary surfacing material shall be submitted for testing, with each sample having minimum surface dimensions of 18 by 18 in. (460 by 460 mm).
- Critical Fall Height Test Procedure: At each specified reference temperature; perform the required number of impact tests to determine performance at the series of reference drop heights. Impact tests at each combination of reference temperature and reference drop height shall be performed on a new sample. The series of reference drop heights should consist of an increasing sequence at intervals of 1 ft (0.3 m). Increment the reference drop height until the impact test results do not meet the performance specified criterion. As a minimum, impact tests must be performed at theoretical drop heights of 1 ± 0.5 ft (0.30 ± 0.15 m) above and 1 ± 0.5 ft (0.30 ± 0.15 m) below the theoretical drop height at which the impact test results approximates the limiting performance criterion. Record the average theoretical drop height, average g-max score and average HIC score at each combination of reference temperature and reference fall height. The critical fall height of the playground surface or surfacing material shall be determined as the maximum theoretical drop height at which impact test results meet the performance criterion at all of the reference temperatures and shall be rounded to the nearest whole foot (0.3 m) equal to or below the actual value.

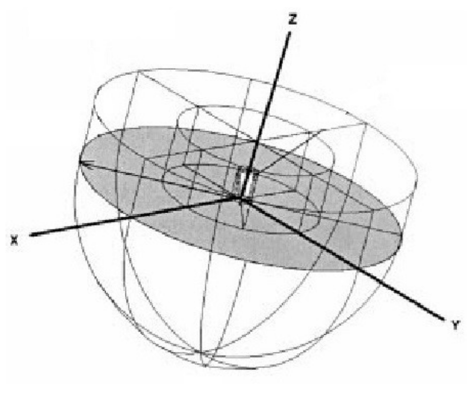


Fig. 2-14 The required Hemispherical missile

2.3.2 ASTM F355 [25]

"Standard Test Method for Shock-Absorbing Properties of Playing Surface Systems and Materials."

- Application field: Playing Surface Systems
- Scope: This test method covers the measurement of certain shock-absorbing characteristics, the impact force-time relationships, and the rebound properties of playing surface systems. This test method is applicable to natural and artificial playing surface systems and to components thereof. Typical playing surfaces are wrestling mats, football fields, soccer fields, playgrounds, and so forth.
- Surface Performance Parameters: The average g-max, average Head Injury Criterion (HIC), average Time to g-max, average Severity Index scores calculated from the last two of a series of three impact tests shall be used as measures of surface performance. Maximum Penetration and Time to Maximum Penetration.
- Performance Criterion: Not specified
- Summary of Test Method: A test specimen is impacted at a specified velocity with a missile of given mass and geometry. A transducer mounted in the missile monitors the acceleration-time history of the impact, which is recorded with the aid of an oscilloscope or other recording device. Optionally, with the use of penetration measuring devices, the displacement history of the impact may also be recorded. The three procedures covered in this test method are as follows. *Procedure A* - uses a cylindrical missile with a circular, flat, metal impacting surface with specified mass, geometry, and impact velocity appropriate for the intended end use. *Procedure B* - uses a missile with a hemispherical, metal impacting surface of specified mass, radius, and impact velocity appropriate for the intended end use. *Procedure C* - uses the ANSI C size metal headform with a specified mass, geometry, and impact velocity appropriate for the end use. For the purposes of this test method, the positioning of the headform shall be such that all impacts

occur on the crown. *Theoretical drop height* shall be calculated from a measurement of impact velocity, v, using the formula $h = v^2/2g$, where g is the acceleration due to gravity.

- Impact Test System: *Testing Machine* - Any type of dynamic testing apparatus that impacts the test material on a massive, rigid anvil with a missile at a prescribed impact velocity and monitors and records the acceleration-time history is acceptable. The anvil mass (impacted base) should be at least 100 times that of the missile. The test apparatus may optionally be designed to test a playing surface in-place. In either case, the test specimen shall have dimensions larger than the impact area of the missile. The test machine and missile shall have sufficient rigidity to eliminate undesirable vibrations in the apparatus that might be recorded on the acceleration-time curve. *Missile* - The mass and geometry for each procedure is referenced in Fig. 2-15. Provision shall be made such that the accelerometer can be securely fastened within ±5° of the vertical axis of the missile. *Recording Equipment* - The recording equipment shall meet the following criteria: *Acceleration-Time* - The selection of the specific acceleration-time recording equipment, including transducers and recorders, is optional.
- Unitary Surfaces: The number of specimens tested as a sample can vary widely, depending upon the intended use of the data. It is recommended that at least two specimens be tested for each set of conditions.
- Procedure: Prewarm the recording equipment as recommended by the manufacturer. Calibrate G time and penetration-time recorder in accordance with the recommended procedure of the equipment manufacturer. Place the specimen under the missile, or orient the dynamic test equipment over the playing surface system. Determine the baseline by preloading the test specimen to 6.8 kPa (1.0 psi) for Procedure A and adjusting the recorder to read zero penetration. When testing at other than ambient conditions, determine the baseline with the sample at the desired test temperature. Set the missile-propelling mechanism to obtain the desired impact velocity. Release the missile, and

record the results in accordance with the recommended procedures of the equipment manufacturers. Make three consecutive drops at intervals of 3 ± 0.25 min.

Procedure	Weight	Geometry
A	9.1 kg ± 50 g (20 ± 0.11 lb)	129 ± 2.0-cm² (20 ± 1.0-in.²) face with a circumference-relieved radius of 2 ± 0.25 mm (0.08 ± 0.01 in.) to eliminate sharp edges
B	6.8 kg ± 50 g (15 ± 0.011 lb)	radius of 82.6 ± 2.5 mm (3.2 ± 0.01 in.)
C	5.0 kg ± 50 g (11 ± 0.011 lb)	specified in Fig.

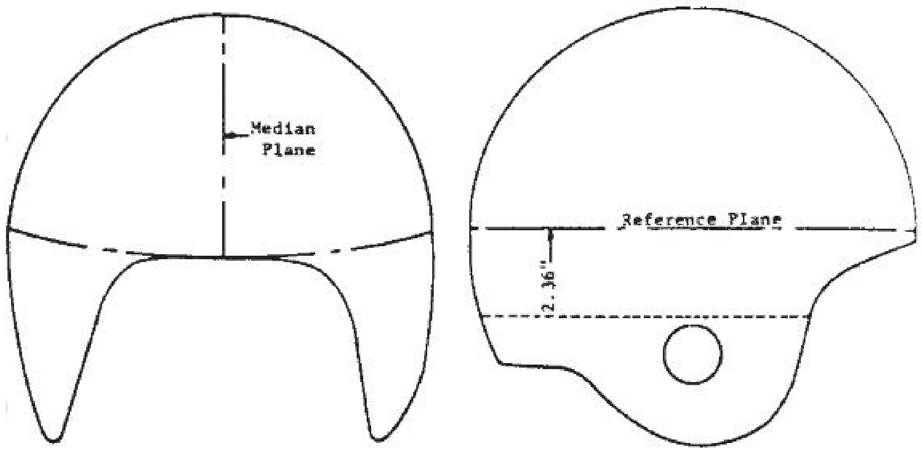


Fig. 2-15 Required Missiles for Procedure A,B,C.

2.3.3 ASTM F1936 [26]

"Standard Specification for Shock-Absorbing Properties of North American Football Field Playing Systems as Measured in the Field."

- Application field: Football Field Playing Systems
- Scope: This specification covers a test method and maximum impact attenuation for all types of installed turf playing systems for North American football.

- Surface Performance Parameters: The average g-max from the last two of a series of three impact tests shall be used as measures of surface performance.
- Performance Criterion: the average g-max at any single test point shall not exceed 200 when tested at a free-fall drop height of 2 ft (61 cm).
- Summary of Test Method: Turf field systems are tested according to this standard and Test Method F 355, Procedure A. A free-fall drop height of 2 ft (61 cm), as measured from the bottom of the missile face to the top of the turf field system shall be used. Any debris or material not part of the surface system shall be removed from the test point location prior to testing. Three successive drops, allowing a 3 min pause between drops, are recorded. The average G max for the tested point will be calculated as the sum of the second and third G max values divided by two and rounded to the nearest whole number. *Theoretical drop height* shall be calculated from a measurement of impact velocity, v, using the formula $h = v^2/2g$, where g is the acceleration due to gravity.
- Impact Test System: ASTM F355 Procedure A
- Surfaces: [26]
- Procedure: [26]

2.3.4 ASTM F2440 [27]

"Standard Specification for Indoor Wall/Feature Padding."

- Application field: Indoor Wall/Feature
- Scope: This specification covers wall padding and padding for other indoor structures. All padding constructions are included. The intended use of this specification is for the qualification of construction designs and comparison of products.
- Surface Performance Parameters: ASTM F1292
- Performance Criterion: ASTM F1292

- Summary of Test Method: ASTM F1292
- Impact Test System: ASTM F1292
- Unitary Surfaces: ASTM F1292
- Procedure: ASTM F1292

2.3.5 EN 1177 [28]

"Impact attenuating playground surfacing. :Determination of critical fall height"

- Application field: Playground Surfacing
- Scope: This standard specifies the requirements for surfacing to be used in playground area and the specific requirements for the areas that need impact cushioning. This specification indicates the factors to be taken into account in the material selection of playground surfacing and provides a test method capable to determine impact cushioning. The specification results the critical fall height for each surface tested, which represents the upper limit of its cushion properties in reducing injury to the head during the use of playground equipment according to EN 1176.
- Surface Performance Parameters: The average Head Injury Criterion (HIC) from the last two of a series of three impact tests shall be used as measures of surface performance.
- Performance Criterion: the average HIC shall not exceed 1000.
- Summary of Test Method: [28]
- Impact Test System: [28]
- Surfaces: [28]
- Procedure: [28]

2.3.6 EN 913 [29]

"Gymnastic equipment - General safety requirements and test methods"

- Application field: Gymnastic Equipment

- Scope: This European Standard specifies general safety requirements and test methods for all pieces of gymnastic equipment intended for use supervised by a competent person and not specified in other, individual standards. This European Standard is not applicable to other sport equipment, playground equipment, stationary training equipment or educational training equipment.
- Surface Performance Parameters: The average g-max from the three of a series of five impact tests shall be used as measures of surface performance.
- Performance Criterion: Shock absorption of top padding - the peak acceleration shall not exceed 500 m/s^2, if not specified in other, individual equipment standards.
- Summary of Test Method: A striker is dropped on to the surface and the deceleration during the impact is monitored.
- Impact Test System: Metal indenter conforming to the essential dimensions shown in Fig. 2-16 and of mass (8 ± 0,1) kg. Means of releasing the striker to allow the indenter to fall smoothly and vertically. Accelerometer rigidly mounted on the axis of the indenter as shown in Fig. 2-16. Instrumentation to record, display and process the accelerometer signals having a channel frequency class, including the accelerometer, of 1 000 Hz in accordance with ISO 6487 and sampling frequency of not less than 10 kHz.
- Surfaces: A piece of protective padding, with its covering if relevant, of minimum length 500 mm and minimum width 500 mm laid on a smooth, solid concrete floor. Alternatively, where feasible, the padding can be tested as attached to the equipment in service.
- Procedure: Raise the indenter to the required height and lock into position. Release the indenter and allow it to fall vertically onto the test piece. Record the signal from the accelerometer throughout the impact. Display the recorded signal and examine the trace to ensure that it contains no spurious peaks, etc. Process the data to obtain the peak

deceleration during the impact, g. Carry out five tests at the same location at intervals of between 1 min and 3 min.

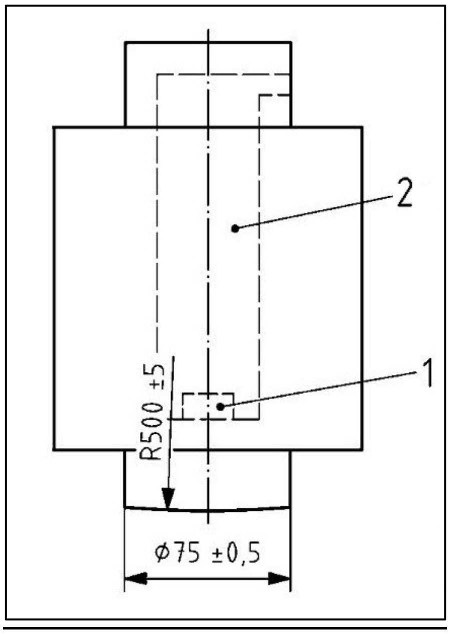


Fig. 2-16 Required Indenter: 1. Accelerometer; 2. Space for mounting the accelerometer

2.4 Design for Sustainability

"Public procurement represents 14% of GDP for the EU as a whole – over 1000 billion Euro. Publicly purchased items come from every sector of the economy – from pencils to power stations – and public procurement can thus have a considerable impact on the marketplace and on sustainable consumption. It is therefore very important that public authorities set an example in this field and seek to procure goods, services and works that do not harm the environment. As Commissioner responsible for the Environment, I am committed to action in this field, in order to clarify and promote the integration of the environment in public purchasing. I am convinced that a deep integration of both areas is possible, without endangering essential Community principles such as those of transparency and non-discrimination. For these reasons I welcome the publishing of this Green Purchasing Good Practice Guide. I appreciate the practical way in which it is written and I hope that other public authorities will be inspired by the examples of concrete action contained in the guide. Local authorities in particular

will find the best practice from the seven towns and cities referred to in the guide useful – 80 % of the EU's population live in towns and cities, and their local authorities can reduce environmental impacts significantly through managing their administrations, public procurement and amenities in an environmentally friendly way."

Margot WALLSTRÖM, Commissioner for the Environment,2000 [30]

2.4.1 Green Purchasing

In a number of environmental fields, traditional environmental policy has led to significant achievements. There are, however, a range of environmental problems still waiting to be solved by the industrialised societies: greenhouse effect, continuing acidification, loss of soils and growing health problems due to air pollutants and dispersed toxic substances. It is obvious that this cannot be done by hierarchic "command and control" protection alone. Therefore environmental experts and recent policy documents unanimously call for integrating the consideration of environmental aspects throughout society and in all fields of policy. Public purchasing (further readings, [31]), as one of the environmentally most significant fields in direct responsibility of governments, plays a significant role in this respect. Green purchasing means basing all purchasing decisions and allocation of contracts on environmental criteria along with other criteria such as price and quality. Not only does green purchasing positively contribute to environmental protection at a local level, it also creates a powerful market demand for greening the production and serves as a model to influence the behaviour of companies, private institutions and households. European local authorities can, to a significant extent, "green" the hundreds of billions of Euro they spend every year for product and services. The key to it is integrating environmental requirements in the procurement of buildings, food for public canteens, health care and cleaning products, fleets, the IT sector, office equipment, material or furniture. In more concrete terms, this implies direct cost savings, avoiding follow-up costs due to a better management, enhancing the quality and the lifespan of products and services and improving staff and citizens' health.

Definitions: Eco, green, greener, environmental, environmentally friendly, eco-responsible: The number of qualifiers used to define products and services, which do not impact the environment as strongly as their conventional counterparts, seems endless and confuses purchasers.

On the assumption that each product always impacts environment, it is quite difficult to find a definition to suit a substantial variety of goods and services. Following, some hints are provided in order to identify "environmentally preferable products" and use this basis as a working definition.

- Life Cycle Assessment (LCA), as the scientifically most reliable method, studies the environmental impact of a product from its design to its disposal, taking into account all the steps in between: raw material extraction, manufacturing, packaging, transport, storage and utilization. In this sense, an "environmentally preferable product" is a product which has an overall minimum environmental impact throughout its lifespan, in comparison to other products or services serving the same purpose and having the same functional qualities. This method of identifying green products is quite sophisticated and, hence, has its limits in that there is a lack of availability of LCAs for each product group and in each particular situation. What's more, going so much into detail, as a rule, LCA can hardly be seen as an appropriate tool to be considered in the whole diversity of purchasing decisions. When unable to refer to a Life Cycle Analysis, purchasers may also identify a greener product by carrying out a simplified study of the product's life cycle as suggested in Fig. 2-17 The two first columns of this table represent the product's characteristics and some of the ecological alternatives proposed to green a product at each stage of its life cycle. The third column identifies the environmental area (material, energy, emissions, waste) on which the choice of environmental alternatives has a positive impact. The last column proposes practical examples of environmental choices to be initiated by purchasers. No matter from where the environmental criteria are taken, a green product/ service has, of course, to fulfil its functions as well as its conventional equivalent. Green products should not be chosen just for the sake of it, but also for economic reasons. This implies a strict assessment of the need they are supposed to fulfil and an evaluation of their cost. The latter goes beyond the very purchase cost taking into account the cost of using and disposing of the chosen item. It may also entail a decision to reduce the amount of products purchased or to fall back on an existing product, instead of purchasing a new one.

Product characteristics	Ecological alternative	Environmental consequence[2]				ACTION - Examples -
		MATERIAL	ENERGY	EMISSIONS	WASTE	
Material composition	Recycled material	X	X		X	Use recycled toilet and towel papers. Procure refuse sacks made of recycled plastic.
	Renewable material	X				Choose recycled concrete or crushed rock rather than gravel as a construction material.
	No toxic substance			X	X	Use chlorine-free paper, PCB-free electronics or PVC-free floor coverings.
Transport	Short distance		X	X		Buy your fruits and vegetables from local producers.
	Transport means		X	X		Make use of rail and boat versus road and plane transport.
Manu-factur-ing	Taking into account the environment	X	X	X	X	Choose a producer which has an environmental management system.
Packa-ging	Reduction	X			X	Prefer recyclable, easily returnable or, if possible, no packaging at all.
Product use	Durability	X			X	Buy long-term guaranteed carpets.
	Repairability / Upgradability	X			X	Choose computers which can be upgraded and do not need to be replaced completely when becoming outdated.
	Compatibility with equipment/user habits	X	X	X	X	When changing for a recycled paper, test its compatibility with copiers and printers before distributing it throughout your organisation.
	Energy requirements		X			Choose low energy light bulbs to save energy (and reduce your annual cost by up to 70%).
	Safety for users	X	X	X	X	Use alternative pesticides or alternative methods of pest control.
End of life	Re-use potential	X			X	Buy refillable toner cartridges for laser and ink jet printers.
	Recyclability	X	X		X	When buying white goods, make sure that they can easily be dismantled and their material recycled.
	Disposal			X	X	Use biodegradable synthetic vegetable-based hydraulic oil for fleet maintenance.

Fig. 2-17 Simple approach of identifying the environmental impacts of products along their life cycle

- A second and more straightforward way for a purchaser to identify a green product are Eco-labels [32]. Purchasing a product labeled “Blue Angel”, “Nordic Swan”, “Austrian Tree” or “EU flower” - to quote only some of the most famous and reliable eco-labels - is a good hint that the purchased item is, in its category, environmentally favorable. The high efficiency of this method is however limited by the large quantity of products without eco-labeling, by the existence of many confusing and more or less significant so-called eco-labels and by the legal restrictions to requiring eco-labeled products in tendering procedures.

- An increasing number of public authorities are implementing an Environmental Management System (EMS). Having been adopted from the private sector, the central idea of this approach is to motivate and enable all parts of administration to improve the environmental performance of their operations. The central achievement of EMS consists in increasing the coherence between political priorities and targets, steps taken and reporting mechanisms on these steps. Without EMS, putting the policies into practice is left to individual officers. Especially with decentralized purchasing structures, it is important that the purchasing policy be implemented at all levels. EMS can have a large impact on the public authority, especially concerning issues of purchasing. Buying goods and services is something that almost everyone is involved in at some time, and awareness is rising continually as policies are being implemented systematically across the whole municipal council. Also, if there are ”pockets of resistance”, pioneers can use EMS to boost ”greener” purchasing. Apart from the authorities’ commitment to implement an EMS, contractors may be obliged to achieve an EMS certificate during the term of the contract. Such certificates are granted for those registering according to a public norm, the two relevant being EMAS and ISO14 001. Large contractors are quicker in taking up the requirements to implement an EMS. Many small contractors, however, still need support. Public authorities can support this process by providing advice on environmental policy and practice to small and medium-sized enterprises.

2.4.2 Design for Environment [33]

In recent years, considerable innovation has gone into product design and management. The aim of innovation is to reduce time taken and resources used in design, production, distribution, and disposal of products with elevated and diverse performance requirements. Environmental awareness is another wave that has simultaneously swept the production process. Over the past decades, this has resulted in strategies to promote environment-friendly production, integrating environmental concerns with product standards. In product development, these new requirements involve a shift away from a conventional approach to an innovative approach. Specifically, it means considerations beyond the sale of the product to the end of the product's useful life and to its retirement. Thus, environmental requirements must lead to innovations toward a successful and "sustainable" product design. A design approach directed at the systematic reduction or elimination of the environmental impacts implicated in the life cycle of a product, from the extraction of raw materials to product disposal, can help.

The implementation of the major principles of environmental protection in industrial practice requires the direct involvement of the product design and development process, as a vector of dissemination and integration of the new environmental needs. DFE originated to facilitate this strategic role and it could be defined as a methodology for the systematic reduction or elimination of environmental impacts implicated in the life cycle of a product, from the extraction of raw materials to product disposal. This methodology is based on an evaluation of the potential impacts throughout the design process. The central theme unifying the various studies on DFE is reduction of the environmental impact of a product across its entire life cycle, from design to disposal. The concept of "reduction of the environmental impact" is not, however, limited to the simple quantification and minimization of direct impacts on the ecosystem. Its implications are wider, extending to the optimization of the environmental performance, which includes the following aspects:

- Reduction of scrap and waste, allowing more efficient use of resources and decrease in the volumes of refuse; reduction in the impact associated with the management of waste materials.
- Optimal management of materials, including the correct use of materials on the basis of the performance required, their recovery at the end of the product's life, and the reduction of toxic or polluting materials.
- Optimization of production processes by the planning of processes that are energy efficient and result in limited emissions.
- Improvement of the product, in particular its behavior during the phase of use, to reduce the consumption of resources or the need for additional resources during its operation.

Analyzing the main aspects related to the concept of "reduction of the environmental impact", it is clear that the environmental assessment of the product-system must be oriented toward a view of the life cycle of a product associated with its physical reality, excluding the conception and development phases, and focusing on the interaction between the ecosphere and all the processes involved in the product's life, from production to disposal. The main impacts of life cycle can be summarized as follows: Consumption of material resources and saturation of waste disposal sites; Consumption of energy resources and loss of energy content of products dumped as waste; Combined direct and indirect emissions of the entire product-system.

In Fig. 2-18 a scheme of elementary transformation process is shown.

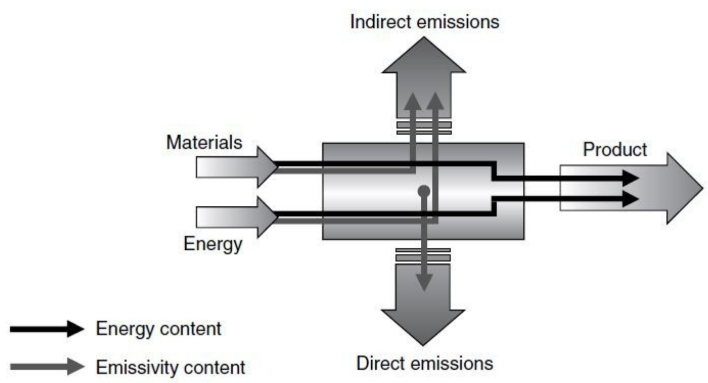


Fig. 2-18 Scheme for the identification of the environmental impact of a process

The energy and emission contents of a material resource are, respectively, understood as the energy expended to produce the material resource and the emissions correlated with its production. While the energy and emission contents of an energy resource are, respectively, understood as the sum of energy expended to produce this energy resource in the form in which it is used in the process and the sum of emissions correlated with its production The distinction between direct and indirect emissions is, respectively, understood as follows the sum of characteristic emissions of the process itself (dependent on the materials, the type of process, and the product of this process) and the sum of the emissions correlated with the production of the resources used by the process, corresponding therefore to the emission content of the resources.

The considerations related to product life cycle, the appropriateness of considering the physical life cycle in environmental analysis, and the basic principles of modeling for elementary activities, are interpreted by the general life cycle flow, each phases interacts with the ecosphere, and it is introduced below:

- Preproduction, where materials and semi-finished pieces are prepared for the production of components.
- Production, involving the transformation of materials, production of components, product assembly and finishing.
- Distribution, comprising the packaging and transport of the finished product.
- Use, including the use of the product for its intended function and any possible servicing operations also.
- Retirement, corresponding to the end of the product's useful life, can consist of various options, from product reuse to disposal as waste.

The life cycle approach can provide a qualitative leap in product development but there's an observation of factors that obstruct environmentally oriented product development in the practice of manufacturing companies: the poor understanding of the environmental impacts of products; the cost-oriented statement of the product development process; and lack of a homogeneous and efficient distribution within the context of the entire development process, of the approach directed at the environmental requirements of products. The first factor linked to the need of producers to address principally those aspects regarding the impact on production sites (consumption of resources and generation of emissions and waste) not directly attributable to products and limited to the context of the production phase alone. The result has been a lack of primary information that could serve as the basis for a strategy aimed at improving the environmental quality of products life cycle. This problem can be resolved by adopting the techniques used in life cycle assessment (LCA).

The Life Cycle Assessment (LCA) is a well-known method of analysis, which enables quantification of the environmental effects associated with a process by means of the identification and quantification of the resources used and the emissions and waste generated as well as the assessment of the impact caused by the use of these resources and the emissions produced. LCA consists of four independent elements:

- Definition of the goal and scope [34]: includes a decision about the functional unit which forms the basis of comparison, the product system to be studied, system boundaries, allocation procedures, assumptions made and limitations. The functional unit can either be a certain service or a product, with the latter being the usual choice for the type of studies reviewed here (e.g., comparison of 1 m3 loose-fill packaging material made of starch polymer versus polystyrene).
- Life cycle inventory analysis [35]: involves data collection and calculation procedures to quantify the total system's inputs and outputs that are relevant from an environmental point of view, i.e. mainly resource use, atmospheric emissions, aqueous emissions, solid waste and land use.
- Life cycle impact assessment [36]: aims at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. One important goal of the life cycle impact assessment is to aggregate outputs with comparable effects (e.g. all greenhouse gases or all acidifying components) by use of so-called characterization factors. This leads to a limited number of parameters, called impact categories. As an optional step, the results by impact categories can be divided by a reference value

(e.g., total greenhouse gas emissions of a country) in order to better understand the relative importance of the various impacts; this step is referred to as normalization. Finally it is, in principle, possible to aggregate the results determined for the various impact categories. However, this valuation step is based not only on scientific facts but also on subjective choices and societal values. So far, there is no generally accepted methodology to translate life cycle inventory data to highly aggregated - let alone, single-score - indicators.

- Life cycle interpretation [37]: is the final step of the LCA where conclusions are drawn from both the life cycle inventory analysis and the life cycle impact assessment or, in the case of life cycle inventory studies, from the inventory analysis only. As an outcome of the interpretation stage, recommendations can be formulated which, for example, may be directed to producers or policy makers.

One of the major problems of the LCA methodology is the difficulty in converting LCI results into environmental impacts and into a single environmental indicator that could be useful for designers during the process of selecting materials. As set out in ISO 14042, the general framework of an LCIA method is composed of several mandatory elements (classification and characterization) that convert LCI results into an indicator for each impact category and a number of optional elements (normalization and weighting) that obtain a single indicator across impact categories using numerical factors based on value choices), as shown in Fig. 2-19 and well described in two different studies on LCIA products application [38],[39].

Following, a specification for every steps is detailed:

- *Classification* is the step in which the data from the inventory analysis are grouped together into a number of impact categories.
- *Characterization* is the step in which aggregation of the impacts within each category takes place. Environmental impacts are converted into a category indicator.

- *Normalization* is the step in which the category indicator result is compared using a reference value (the average yearly environmental load in a country or continent, the number of inhabitants, etc.). The category indicator is divided by the reference.
- *Weighting* is the step in which the impact category indicator results are multiplied by weighting factors and are added to form a total score. Weighting can be applied to normalized or non-normalized scores.

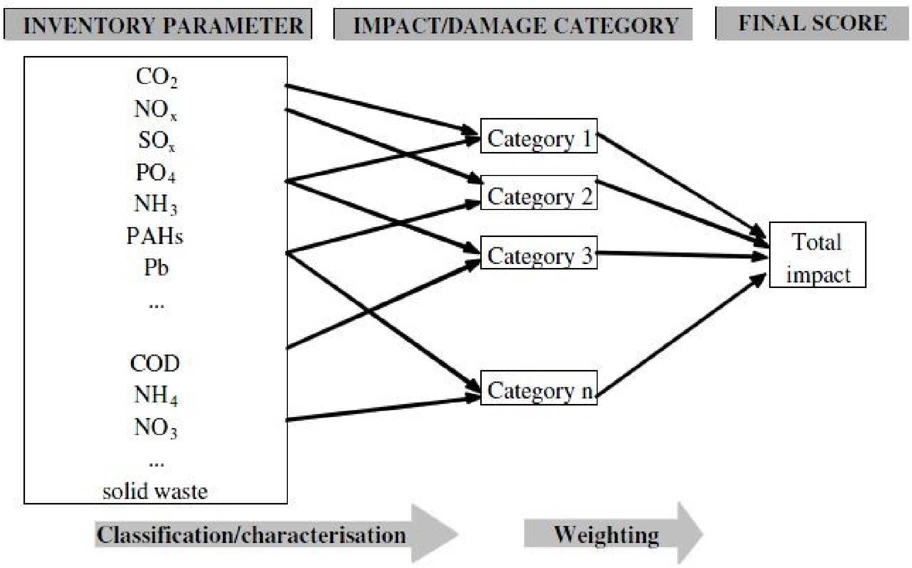


Fig. 2-19 LCIA Approach

Several reviews of weighting methods can be found in the literature, one of the most used is Eco-indicator '95 [40] and the updated Eco-indicator '99 [41].

- The Eco-Indicator '95 method was developed under the Dutch NOH Programme by Pre´ Consultants (The Netherlands). The characterization factors match those considered in the CML method, although specific categories for toxicity have been included, namely, heavy metals, carcinogenic substances, winter smog and pesticides. Normalization is based on 1990 effects levels for Europe, excluding the former USSR. The weighting principle is based on a mixture of the distance-to-target approach and the damage approach: weighting factors are calculated as the ratio of the actual inventory value for each effect category, with additional subjective weighting to represent significance on human health and ecosystem impairment.

- The Eco-Indicator ‘99 method is a new version of EI ’95. This new version was based entirely on the damage approach and links inventory results into three damage categories: human health, ecosystem quality and resources. The normalization procedure considers the total inventory of mass and energy used in the whole of Western Europe by one person per year (population of 495 million assumed). The weighting procedure was carried out by means of a written panel procedure among Swiss LCA interest group. Three perspectives can be applied: individualist (higher weight to human health), egalitarian (higher weight to ecosystem quality) and hierarchist (equal weight distribution).

An example of life cycle inventory of different polymer materials (PVC, PE and PP) used for packaging purposes is being shown. LCI information is based on the ‘‘Eco-profiles of the European Plastic Industry’’ developed for the Association of Plastics Manufacturers in Europe (APME). The inventory table includes emissions from raw material production, energy production, production of semi-manufactures and auxiliary materials, transport and the production process of the polymer materials. A detailed description of the system, including the life cycle inventory data, can be consulted from BUWAL 250 [42]. All the shown data refer to 1 kg of PVC, PE and PP. An excerpt from the inventory results showing the most important emissions for each material is shown in Fig. 2-20.

In a study on Environmental assessment of bio-based polymers [43], twenty life cycle assessment are reviewed and excerpts for polymer products in term of life-cycle energy contents and emissions are shown by using most common applied Life Cycle Inventory Databases. Those data and were at basis of further developed results that are being shown following in the thesis project.

	PVC	PE	PP
Resources			
Natural gas (m^3)	330	620	250
Crude oil (kg)	370	520	830
Iron (kg)	0.4	0.2	0.3
Bauxite (kg)	0.22	0.3	0.4
Emission to air			
Benzene (g)	2	4	4.4
PAHs (g)	0.02	0.016	0.017
C_xH_y aromatic (g)	7.3	9	10
HALON 1301 (g)	0.037	0.075	0.092
C_xH_y halogenated (g)	0.00036	0.00023	0.00021
Methane (g)	5700	4200	3400
Non methane VOC (g)	14,300	16,800	9600
CO_2 (g)	1,940,000	2,200,000	1,800,000
CO (g)	2700	800	700
Ammonia (g)	1.5	1	0.83
HF (g)	8.8	1	1
N_2O (g)	6.8	6	5.7
HCl (g)	230	60	40
SO_x as SO_2 (g)	13,000	7000	11,000
NO_x as NO_2 (g)	16,000	11,000	10,000
Pb (g)	0.12	0.088	0.088
Cd (g)	0.014	0.016	0.018
Mn (g)	0.05	0.029	0.027
Ni (g)	0.85	1	0.96
Emission to water			
BOD (g)	80	150	60
COD (g)	1100	1000	400
AOX (g)	0.03	0.06	0.075
Suspended substances (g)	2400	400	200
Phenols (g)	1.1	1	2.6
Toluene (g)	1	2	2.3
PAHs (g)	0.1	0.21	0.25
C_xH_y aromatic (g)	7.3	14	17
C_xH_y chloro (g)	10	0.02	0.021
Fats/oil (g)	50	100	40
DOC (g)	1000	20	30
TOC (g)	480	100	300
NH_4^+ (g)	17	5	10
Nitrate (g)	10	5	20
Kjeldahl-N (g)	2.4	6	6.9
N-tot (g)	3	10	10
As (g)	1.3	0.28	0.26
Cl^- (g)	40,000	120	800
Cyanide (g)	0.04	0.066	0.08
Phosphate (g)	38	5	13.5
Sulphate (g)	4300	10	1700
Sulphide (g)	0.25	0.5	0.61
Hg (g)	0.0017	0.002	0.0013
Solid emissions			
Production waste (kg)	129.54	34.2	31.2

Fig. 2-20 An excerpt of the LCI inventory considered for 1 kg of PVC, PE and PP from BUWAL 250 [42]

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3.
Experimental Program

Background research efforts previously handled in chapter 2, regarding sports area safety topic, have shown potential and observed injuries for sports activities participants. In order to evaluate safety requirements compliance of actually used protective devices in sports area, three different impact testing experimental phases on several polymer-based foam product configurations were followed in Sports Equipment and Technology Department (SGT) of Chemnitz University of Technology. A special impact testing apparatus was designed and built according International Sports Safety Standards units technical requirements and further head impact dynamics and biomechanics approaches were integrated in order to achieve an exhaustive testing procedure toward a proper head injury risks evaluation. Impact tests were performed during three different timing periods, each referred to the shown Papers at the bottom of the thesis, whose names were attributed as follows:

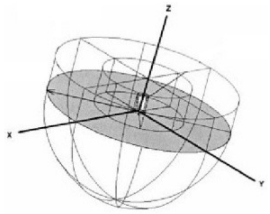
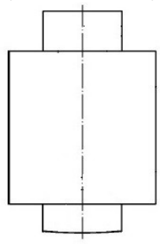
- Experimental Program Phase 1 – Pilot Investigation (Paper A)
- Experimental Program Phase 2 – Head Injury Risks Evaluation (Paper B)
- Experimental Program Phase 3 – Toward a New Safety Approach (Paper C)

In this chapter, each experimental program phase is detailed in its own paragraph where materials, methods and results sections of the related paper are eventually integrated with new or missing subjects.

A common impact testing apparatus to all of the impact testing phases is going to be shown next paragraph.

3.1 Impact Testing Apparatus

The three phases of the experimental program were pointed on impact attenuation properties evaluation of several foam configurations through low-velocity impact tests. A typical low-velocity impact testing apparatus draft was shown in "Background – International Sports Safety Standards" paragraph, Fig. 2-12. In the same chapter section, several international sport standards were analyzed in order to underline scopes, performance parameters and criterions, general measurement systems definitions and requirements, testing procedures adopted. In particular, the European EN 913 and EN 1177, the American ASTM F1292 were took deeply into account in order to realize, by designing and manufacturing processes, a flexible apparatus that was capable to carry out tests according to all of the three cited specifications. In following Tab. 3-1, a list of the previous standards units technical definitions and requirements is show as comparison:

Apparatus Unit	**Standard**		
	ASTM F1292	**EN 1177**	**EN 913**
Missile Definitions	a) *Missile* – rigid object of specified mass with a hemispherical surface of specified radius. b) *Support assembly* – a handle or ball arm,rigidly attached to the missile as a means of connecting it to an external guidance system c) *Drop Assembly* – is the combined mass of the missile, and support assembly	Hemispherical Indenter	Metal Indenter, Striker
Missile Requirements	Hemispherical Shape  - Diameter: 160 mm - Total Mass: 4.6 kg - Support assembly Maximum Mass = 1.4 kg	Hemispherical Shape - Diameter: 160 mm - Total Mass: 4.6 kg	Cylindrical Shape  - Diameter: 75mm - Total Mass: 8 kg

Missile Requirements	• The missile may include cavities and additional components required to accommodate the attachment of sensors or to attach a supporting assembly. The form of any cavities or additional components shall be generally symmetrical about the Z-axis of the level missile such that center of mass lies within 0.08 in. (2 mm) of the Z-axis and the moments of inertia about any two horizontal axes do not differ by more than 5 %. • Roughness: 25 µm	• Accelerometer rigidly mounted on the vertical axis • Roughness: Class N11 According ISO 1302 Standard	• Accelerometer rigidly mounted on the vertical axis • Roughness: NOT SPECIFIED
Acceleration Measurement System Definitions	• Accelerometer: A trasducer for measuring acceleration • Trasducer: the first device in data channel, used to convert a physical quantity to be measured into a second quantity (such as an electrical voltage) which can be processed by the remainder of the channel. • uniaxial accelerometer: a transducer used to measure the component of acceleration relative to a single spatial axis.	Uniaxial Accelerometer	Accelerometer
Acceleration Measurement System Requirements:			
Accuracy	±1% of the true value	Not Specified	Not Specified
Frequency Response	All acceleration data channels, before signal filtering, shall have a flat frequency response ±0.1 dB in a range extending from below a maximum of 1.0 Hz to above a minimum of 2000 Hz.	Not Specified	Not Specified

Channel Frequency Class	All acceleration data channels, including signal filtering, shall conform to the requirements of a Channel Frequency Class 1000 data channel, as specified by SAE Recommended Practice J211, with the additional requirement of increased accuracy in the range from 1 to 1000 Hz	Instrumentation to record, display and process the accelerometer signals having a channel frequency class, including the accelerometer, of 1000 Hz in accordance with ISO 6487	Instrumentation to record, display and process the accelerometer signals having a channel frequency class, including the accelerometer, of 1000 Hz in accordance with ISO 6487
Location	An accelerometer shall be rigidly attached at the center of mass of the missile with its axis of sensitivity aligned (65°) with the missile's Z-axis. The sensing axis of the accelerometer shall pass through the center of mass of the missile.	Accelerometer rigidly mounted on the axis of the missile	Accelerometer rigidly mounted on the axis of the indenter
Sensitive Range	Accelerometers shall have a minimum sensitive range from ±500 g and be capable of tolerating accelerations of at least 1000 g along any axis.	Not Specified	Not Specified
Anti-aliasing Filter	To prevent aliasing in the digitized acceleration data, the acceleration signals shall be filtered with an analog low pass filter prior to digitization. The anti-aliasing filter shall have a corner frequency of 5000 ± 500 Hz or a maximum of 0.25 times the single channel sampling rate.	Not Specified	Not Specified
Data Channel Filter	Digitized data shall be filtered using a 4th order Butterworth Filter. An analog filter may be substituted provided it has 4-pole characteristics and conforms to the data channel specification.	Not Specified	Not Specified

Resolution	The conversion from analog accelerometer signal to digital data shall be accomplished with a digitizer having a resolution of no less that twelve bits spanning the range ±500 g.	Not Specified	Not Specified
Sample Rate	Minimum sampling rate of the recording device shall be 20.0 kHz per accelerometer channel.	Not Specified	Sampling frequency of not less than 10 kHz
Capacity	The digitizer shall be capable of recording and storing data continuously for a minimum of 50 ms, beginning at least 5 ms before onset of the impact and ending no earlier than 5 ms after the cessation of the impact.	Not Specified	Not Specified
Display	The recording system shall have the capability of displaying the recorded acceleration-time data in order to allow inspection by the operator. A graphical display is recommended, but a tabular printout or other form of display is acceptable. The display shall allow inspection of all the data points recorded from at least 5 ms before the onset of impact until no less than 5 ms after cessation of the impact. The display shall show acceleration data in a manner that allows inspection of all data points lying in the acceleration range from -10 g to a value that exceeds the maximum recorded acceleration value.	Not Specified	Not Specified

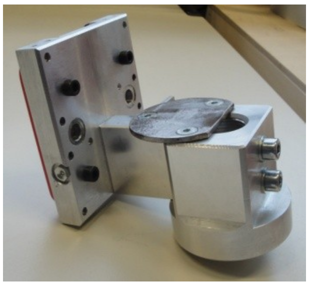
Guidance Mechanism System Definitions	Guided impact test: an impact test in which the trajectory of the missile is restrained by rails, wires, or other mechanism or structure.	Guidance System in order to guide the missile	Means of releasing the striker to allow the indenter to fall smoothly and vertically
Guidance Mechanism System Requirements	the missile may be connected to low friction guides (such as monorail, dual rails, or guide wires) using a follower or other mechanism in order to constrain the fall trajectory of the missile to a vertically downward path. The guidance system must allow the missile to be leveled prior to a drop and must maintain the missile in a level (65°) attitude during the drop. The guidance mechanism shall be constructed in a manner that does not impede the trajectory of the missile during its fall or during its contact with the surface being tested; other than necessary impedance caused by friction in the guidance mechanism..	Not Specified	Not Specified
Drop height Measurement System Requirements	• Drop Height Control Mechanism: The guidance mechanism or the support structure shall incorporate a means of repeatedly positioning the missile at a predetermined drop height. • Release Mechanism: A manual or electronically operated quick-release mechanism shall be provided as a means of initiating a drop of the missile. The operation of the release mechanism shall not influence the fall trajectory of the missile following release. • Drop Height	Not Specified	Indenter locked into position at the required height

	Measurement: A means of repeatably determining the missile's drop height with a resolution of 1 in (25mm) and to an accuracy of ±1 % of the true value is required.		
Temperature Measurement System Requirements	Temperature Measuring Device: The thermometer, digital temperature gage, or other sensor used to measure surface temperature shall have a functional range of at least from -20 to +130°F (-7 to +54°C), a resolution of 1.0°F (0.6°C), and an accuracy of ±1.0°F (0.6°C). The temperature sensor shall be capable of penetrating the playground surface to a depth of at least one inch.	Impact testing at the temperature of 20 ±5 °C	Condition the test piece for a minimum of 3 h at the test temperature of (23 ± 2) °C
Velocity Measurement System Requirements	The velocity measuring system may consist of a light gate device to measure the time an opaque flag interrupts a light sensor or other appropriate means. The velocity measuring device shall not interfere with or impede the trajectory of the missile and shall be capable of recording impact velocity with a resolution of 0.1 ft s^{-1} (0.03 m s^{-1}) and an accuracy of ±1 % of the true value. The velocity of the missile must be determined by measuring the velocity immediately prior to the onset of an impact; at a point in the missile's trajectory no more than 2.0 in. (51 mm.) above the first point of contact between the missile and the surface under test.	Not Specified	Not Specified

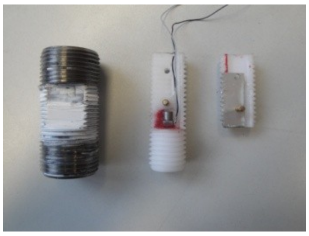
Tab. 3-1 Units Technical Definitions and Requirements According ASTM F1292, EN 1177, EN 913

The American ASTM F1292 was the most referenced and used specification concerning playground equipment and other application sports standards. Many studies on impact testing topic has been done through this standard as reported in the "Background – Bibliography" references. Referring to the technical requirements and definitions list in Tab. 3-1, the ASTM F1292 appeared to be the most complete specification for every single units and parameter measurement systems shown (i.e., missile parts, acceleration measurement system settings, guidance system, velocity measurement system, etc). From technical requirements point of view, this American standard appeared to ensure more accuracy (than the European ones) in results that have being achieved through impact testing experimental program. For this reason, a unique impact testing apparatus was designed following ASTM F1292 measurement system recommendations and capable to perform impact tests according to EN 913 and EN 1177 as well. To this end, an assembly of three parts (named "Drop Assembly") was designed in order to ensure the interchangeability of the hemispherical missile (ASTM F1292, EN 1177) with the cylindrical one (EN 913) through a threaded shaft (that contained the accelerometer), which diameter ensured coupling of both missiles with the supporting assembly:

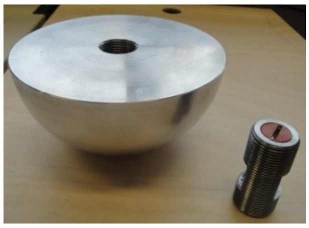
- ✓ Drop Assembly according ASTM F1292 and EN 1177



Support Assembly

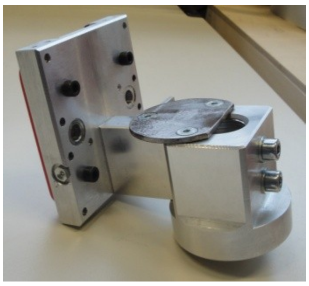


Threaded Shaft

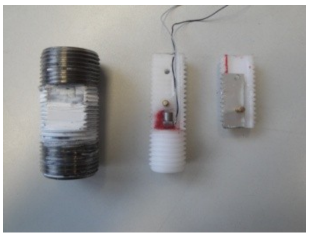


Hemispherical Missile

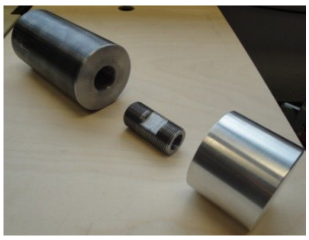
- ✓ Drop Assembly according EN 913



Support Assembly

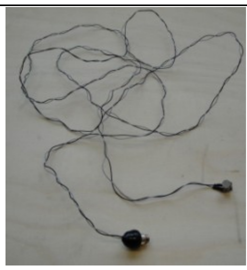
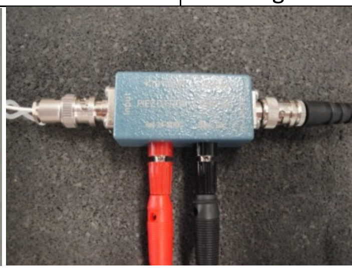
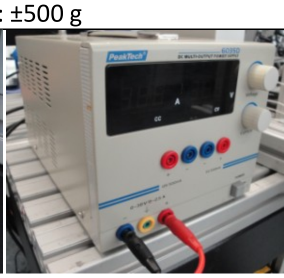
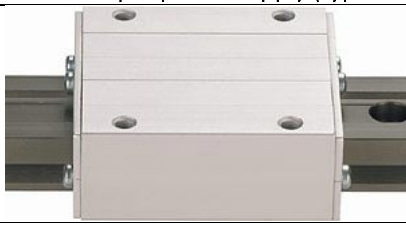


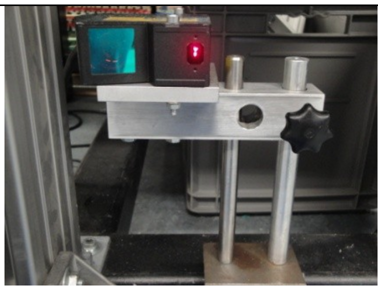
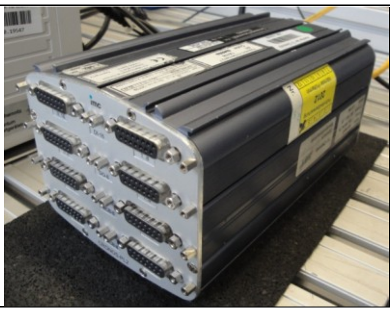
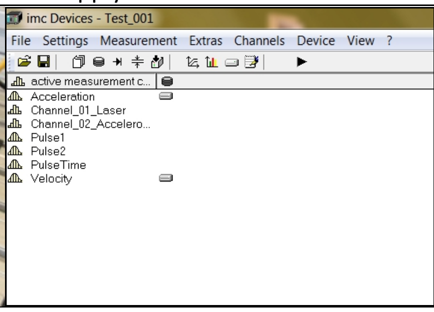
Threaded Shaft



Cylindrical Missile

In Tab. 3-2 all the designed and manufactured apparatus units are shown by specifying each technical settings. The expected flexibility to different procedures was achieved by using the same guidance system, acceleration, drop height and velocity measurement system, recording and display system. In Fig. 3-1 the working impact testing apparatus is shown.

<table>
<tr><th rowspan="2">Apparatus Unit</th><th colspan="3">Standard</th></tr>
<tr><th>ASTM F1292</th><th>EN 1177</th><th>EN 913</th></tr>
<tr><td>Drop Assembly</td><td colspan="2">
Standard Mass: 4.6 ± 0.05 kg
Measured Mass: 4623.70 g
Roughness: 25 µm</td><td>
Standard Mass:
4.6 ± 0.05 kg
Measured Mass:
7991.25 g
Roughness: 25 µm</td></tr>
<tr><td>Acceleration Measurement System</td><td colspan="3"> 
Piezoelectric Uniaxial Transducer and Piezotron Coupler
(type: 8614A500M1, Kistler Holding AG)
Sensitivity range: ±500 g</td></tr>
<tr><td>Drop Assembly Release Mechanism</td><td colspan="3"> 
Magnet and DC multi-output power supply (type: Peakteak 6035D)</td></tr>
<tr><td rowspan="2">Guidance Mechanism System</td><td colspan="3"></td></tr>
<tr><td colspan="3">Linear guide carriage (type DryLinl T - Lubrification free gliding elements made of iglidur© J - IGUS GmbH)</td></tr>
</table>

<table>
<tr><td>Velocity Measurement System</td><td> 
Laser Displacement sensor ± 40mm (type LK-G152, Keyence Corp) and Power Supply</td></tr>
<tr><td rowspan="2">Recording and Displaying System</td><td> 
</td></tr>
<tr><td>Frequency-to-Voltage Converter (type IMC CRONOS PL)
Software type: IMC DEVICE CONTROL VER. 2.7</td></tr>
</table>

Tab. 3-2 Impact testing apparatus units

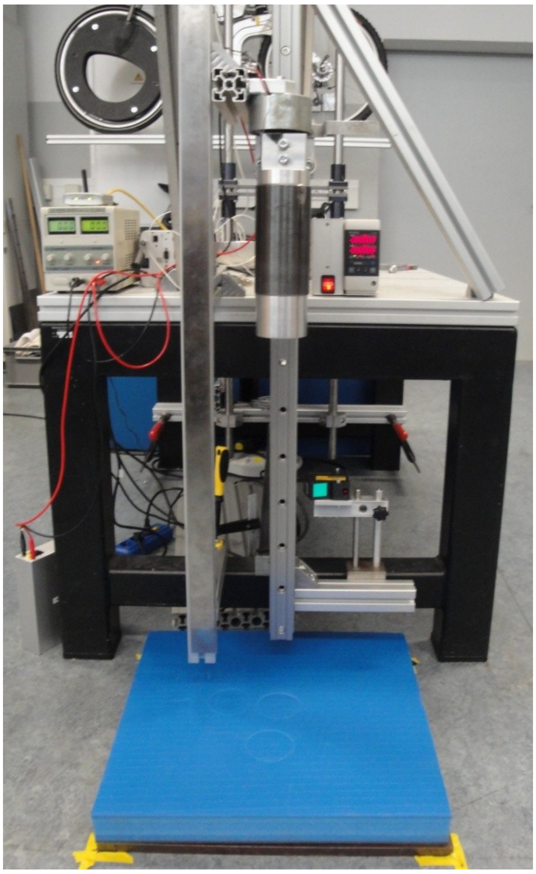


Fig. 3-1 The working impact testing apparatus

3.2 Experimental Program Phase 1 – Pilot Investigation (Paper A)

This first experimental program phase showed preliminary results of the main research project aimed to improve passive safety of gymnastic equipments. To assess the impact attenuation performances of several protective devices actually used in sports area, mainly realized with polymer-based foams, impact testing standards were applied. In particular, a pilot investigation allowed to collect first experimental results and obtained by using a new testing apparatus (Fig. 3-1) developed at the *Sports Equipment and Technology (SGT)* Lab of Chemnitz University of Technology. Impact attenuation performances of two protective devices, realized with polymer-based foams, were analyzed through an hybrid impact testing protocol according the EN 913 procedure and ASTM F1292 technical units requirements.

Main goals achieved:

- The comparison of test standards revealed lack of specifications in EN 913 standard, that has to be modified (i.e., friction influences in guidance system, exact interval time period between consecutive impacts, head injury risks evaluation)
- The parameter of theoretical drop height was introduced to compare experimental results collected in Chemnitz laboratory with others previously collected in an accredited laboratory. Therefore, the referenced behavior of acceleration trend under multiple-impact loads were confirmed by results achieved.

Finally, sources of uncertainty and reasons of unfair comparison were discussed in order to advice sports area managers and technicians about the consequences of their choices in evaluating performances of passive safety devices for gymnastic equipment by adopting the EN 913.

For a complete dissertation on materials and methods used, experimental program data sheets achieved and discussion, please refer to “Paper A”, p. 88.

3.3 Experimental Program Phase 2 – Head Injury Risks Evaluation (Paper B)

This second experimental program phase aimed to solve previous lacks shown in EN 913 procedure by adopting the most referenced impact testing specification provide by the ASTM F1292. A new performance parameter, the Head Injury Criterion (HIC), was introduced in impact testing experiments carried out by using the flexible apparatus shown in Fig. 3-1. Several polymer-based protective devices were tested. Two different indexes, a safety and eco-sustainability ones, were introduced in order to help sports area technicians in a optimal choice of protection devices point of view. This experimental program was also widely described in the report [1].

<u>Main goals achieved</u>:

- The results of the impact tests showed that, in order to optimize the choice of protection devices on the base of impact absorption properties, a joint monitoring of acceleration peak, drop height and Head Injury Criterion (HIC) parameters, it is needed.
- Due to a dependence of devices impact attenuation properties on drop height magnitude, a numerical definition of a critical fall height of use (i.e., by measuring impact energy amount that athletes could be experienced) it was suggested to be given.

For a complete dissertation on materials and methods used, experimental program data sheets achieved and discussion, please refer to “Paper B”, p. 96.

3.3.1 Further Results

This paragraph aims to show further results that are not included in “Paper B” thesis section. Referring to “Paper B – Materials and Methods”, a further experimental program was followed on the same specimen architectures shown in Tab.2 (A,B,C,D,E) and according with a different impact testing procedure: the EN 913 procedure, in fact, was adopted by replacing the hemispherical missile (previously used in the paper for comply the ASTM F1292 procedure) with the cylindrical missile on the common apparatus made in Chemnitz Laboratory. The same impact testing parameters shown in Tab.3 were monitored on different impact testing trial series of 5 drops, useful to finally achieve the critical fall height that produced an average acceleration (on the last three of the total five impacts) lesser than the EN 913 performance criterion of 50g. In following Tab. 3-3 a general list of results is given for all of the architectures under test and, in Fig. 3-2, architectures performances in terms of critical fall height are shown for new results achieved (EN 913 procedure – cylindrical missile) and previous results achieved (ASTM F1292 – hemispherical missile), as comparison.

Variable	Arch.A	Arch.B	Arch.C	Arch.D	Arch.E
h_m (m)	0,790	0.750	0.630	0.500	0.430
v_m (m/s)	3,44	3.44	3.14	2.79	2.56
a_m (g)	45.28	48.09	47.76	47.55	46.77
h_{th} (m) = h_{cr}	0.605	0.603	0.506	0.396	0.336
v_{th} (m/s)	3.94	3.84	3.52	3.13	2.90
r_v	0.873	0.896	0.892	0.891	0.883

Tab. 3-3 Critical data sheet for Architectures A,B,C,D,E (EN 913 procedure - cylindrical missile)

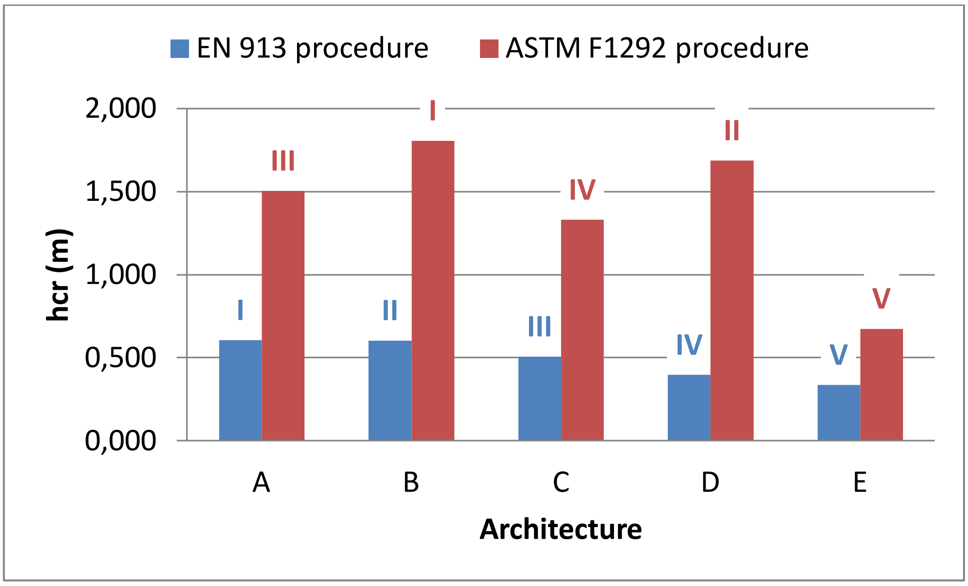
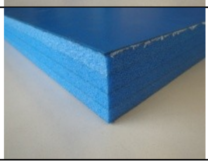
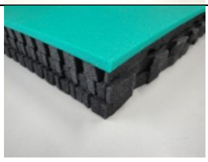
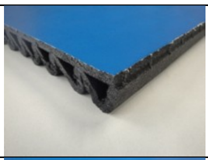
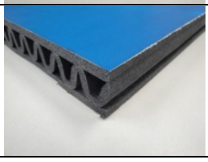


Fig. 3-2 Critical Fall height architectures performances according EN 913 and ASTM F1292 procedure

Critical fall height according ASTM F1292 appeared to be always greater than those related to the EN 913 due to an higher performance criterion (in term of acceleration peaks - 200 g vs 50 g) to be achieved. Interestingly, architecture A,D has shown different performances in the two rankings underlined in Fig. 3-2. From optimal device choice point of view, products that appeared to comply with the best safety performances (higher critical fall height are the better) according the EN 913, don't confirm this agreement by changing standard procedure (ASTM F1292). Therefore, in order to properly compare this last two standard procedure performances, impact tests from the same drop height (by equating impact energies) it is recommended to perform.

Finally, in Tab. 3-4, a comparison between several architectures is given by percentage variations of critical fall height performances in order to underline covering, top and down layer influences:

Covering Influence					
Architecture Specifications					Critical Fall Height (m)
Photo	Material	Layers Number	Density (kg/m^3)	Covering	
	PE	4	1° - 30 2° - 30 3° - 30 4° - 30	NO	0.453
	PE+PVC covering	4	1° - 30 2° - 30 3° - 30 4° - 30	YES	0.506
Percentage Variation					+ 11.74 %
Top Layer Influence					
Architecture Specifications					Critical Fall Height (m)
Photo	Material	Layers Number	Density (kg/m^3)	Covering	
	PE	4	1° - 30 2° - 30 3° - 30 4° - 30	NO	0.328
	PE+PVC covering	5	1° - 60 2° - 30 3° - 30 4° - 30 5° - 30	NO	0.598
Percentage Variation					+ 82.13 %

Down Layer Influence					
Architecture Specifications					Critical Fall Height (m)
Photo	Material	Layers Number	Density (kg/m^3)	Covering	
	PE+PVC covering	2	1° - 30 2° - 30	YES	0.235
	PE+PVC covering	3	1° - 30 2° - 30 3° - 30	YES	0.336
Percentage Variation					+ 42.96 %

Tab. 3-4 Covering, Top and Down layer influences

All of the factors introduced (covering, top and down layer) increased architecture performances in term of critical fall height. The major contribution (+ 82.13 %) is given by a top layer that overlap a typical sandwich core section made of irregular (not full) layers. In a sandwich design process it is recommended to adopt these last shown solutions.

<u>Safety Index</u>

As deeply described in "Paper B – Results and Discussion", in order to optimize the choice of protection devices from impact absorption properties point of view, it is needed to consider together acceleration peak, drop height and Head Injury Criterion (HIC) values during impact testing procedures. It was also shown that device performances depend on drop height magnitude: for each sport discipline, it is well-recommended to define the fall height of use, or the equivalent maximum impact energy amount which could be experienced by athletes during sport practice.

To this end and referring to a particular protective device architecture, this expected joint monitoring of the acceleration peak, the HIC and drop height parameters, opportunely referred to real sport collisions, could be realized by introducing a new safety index "S" [1] where each registered parameter value (performances of the architecture under study in term of measured acceleration peak and measured HIC from a measured drop height) is weighted on its performance criterion (for acceleration and HIC) and the critical fall height, which formulation is defined as follow:

$$S = f(K_1; K_2; K_3) \tag{9}$$

Where:

$$\begin{aligned} K_1 &= HIC_m; \quad 0 < K_1 < 1000 \\ K_2 &= \frac{a_m}{a_{cr}}; \quad 0 < K_2 < 1 \\ K_3 &= \frac{h_m}{h_{cr}}; \quad 0 < K_3 < 1 \end{aligned} \tag{10}$$

An explicit formulation of S-index is going to be well-explained as following. For each specimen (architecture) under study, the parameters HIC_m and a_m are the outcomes of an impact test from a fixed drop height h_m that could coincide with a fall height of use in a special sport application. The parameter a_{cr} is the performance criterion in term of acceleration (equal to 200 g with an hemispherical missile) from the critical fall height h_{cr} of the specimen. Previous indexes shown in (10) range from 0 to 1000 that is the performance criterion of HIC (K_1), from 0 to 1 when the measured acceleration coincides with the specimen critical one (K_2), from 0 to 1 when the impact test is performed from a drop height that coincides with the specimen critical one (K_3). By dividing each K-index interval in 4 sub-intervals is possible to build a rating scale where an amount of points is assigned to each K-index sub-interval, as in following Tab. 3-5:

Points	**K_1**	**K_2**	**K_3**
10	0-299	0-0,25	0-0,25
6	300-544	0,25-0,5	0,25-0,5
3	545-755	0,5-0,75	0,5-0,75
1	756-1000	0,75-1	0,75-1

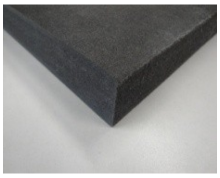
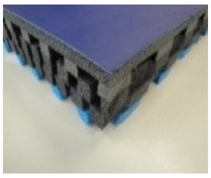
Tab. 3-5 K-indexes sub-intervals and severity points-based system evaluation

Where each amount of these shown points represent the severity of the impact that is maximum in correspondence of 1 point (minimum level of safety offered by the specimen under study) and minimum in correspondence of 10 points (maximum level of safety offered by the specimen under study). A first hypothesis on the explicit formulation of S-index could be fixed as a sum of points achieved by K-indexes. In this way, S-index achieves 4 ranges of points (intervals) that could be seen as global level of safety of the tested specimen and a new rating mechanism (through number of stars) define the maximum level (5) and minimum level (1), as in following Tab. 3-6:

Safety Index “S” intervals	Evaluation
30-26	★★★★★
22-25	★★★★
18-22	★★★
13-17	★★
3-12	★

Tab. 3-6 S-Index sub-intervals and safety stars-based system evaluation

When tested in accordance with “Paper B – Impact testing protocol” a particular architecture is characterized by impact testing outcomes in term of measured acceleration peak, HIC and critical fall height, as in “Paper B – Results – Tab.4”. Let suppose to investigate safety level of Architecture A,C,D shown in Paper B, when these latter are required to be installed in Football fields. Authors Mc Intosh et Al. [2] have shown that a football player, during his practice, could be exposed to an amount of impact energy equal to 55 J that correspond to a fall height of 1.210 m (W=mgh where W=55 J; m (mass of missile)=4.6kg and g=9.806 m/s^2). Impact test results shown in Paper B has established that Architecture A,C,D have reached critical fall heights of 1.503 m, 1.329 m, 1.662 m, respectively, in correspondence of the critical acceleration (a_{cr}) of 200g. New impact tests on the same architectures and from the football field required drop height of 1.210 m, has given new outcomes in term of measured acceleration a_m and HIC_m , shown in following Tab. 3-7. Starting from this collected data, is possible to apply equations (10) and to obtain Safety Index S evaluation through Tab. 3-5, Tab. 3-6, as in following Tab. 3-7:

Football Field Fall Height - h = 1,210 m			
Parameter	Architecture		
	D  h_{cr} = 1,662 m a_{cr} = 200 g	C  h_{cr} = 1,329 m a_{cr} = 200 g	A  h_{cr} = 1,503 m a_{cr} = 200 g
a_m	131 g	149 g	115 g
HIC_m	576	581	393
K_1	576 (3 points)	581 (3 points)	393 (6 points)
K_2	0,655 (3 points)	0,745 (3 points)	0,575 (3 points)
K_3	0,73 (3 points)	0,91 (1 points)	0,81 (1 points)
S	9 points	7 points	10 points
Safety Evaluation			

Tab. 3-7 An example of Safety level evaluation of architecture A,C,D in football fields application

All the previous tested architectures achieved the same (minimum) level of safety correspondent to the assigned one star. In this case, it is expected to select the best architecture by adopting different indexes or criterion: for example, from eco-design point of view, in Fig.12 of Paper B, Architecture C achieved the best ratio between its performance and weight. Thus, It should be selected for this case study.

3.4 Experimental Program Phase 3 – Toward a new Safety Approach (Paper C)

This third and last experimental program aimed to sum up all the achieved goals in last impact testing experiences by defining requirements, toward a new impact testing procedure, useful to improve passive safety of protective sports equipment and devices. In order to evaluate potential brain damage as consequence of athletes concussion, a comparison between standard testing procedures were done through biomechanical indexes application and missile shape influences evaluation. The EN 913 (using a cylindrical missile) and EN 1177 (using a hemispherical missile) procedures were alternatively applied on a huge number of specimens (made of polymer based foam) through the same flexible impact testing apparatus built in *SGT* laboratories.

<u>Main goals achieved</u>:

- In correspondence of the EN 913 procedure critical fall heights (those ones that produced 50g acceleration and no brain damage), not equal to zero brain injury probabilities were registered, when impact tests were performed from equivalent drop heights (by equating impact energies) through the EN 1177 procedure and brain trauma degree evaluation algorithm.
- Results achieved through the EN 1177 procedure have shown brain injury risks underestimation due to a not proper performance criterion concerns. For this reason, a joint monitoring of acceleration peak, drop height and Head Injury Criterion (HIC) parameters, it is required to be effected.
- Finally, from impact testing reproducibility point of view, a fixed tolerance on measured/theoretical velocity ratio and declared percentage variation of measured/nominal acceleration peaks, it is recommended to be given.

For a complete dissertation on materials and methods used, experimental program data sheets achieved and discussion, please refer to “Paper C”, p. 103.

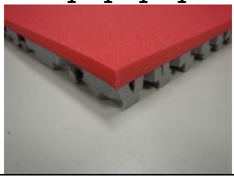
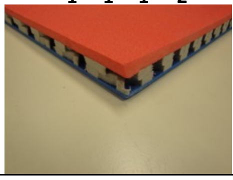
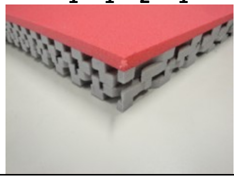
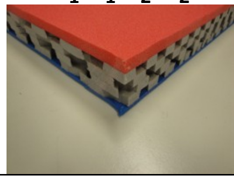
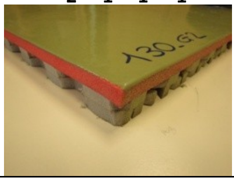
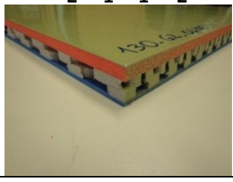
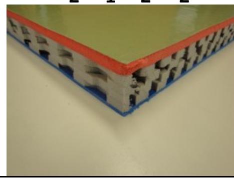
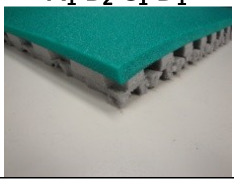
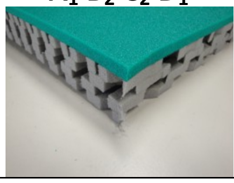
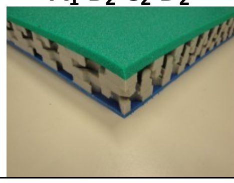
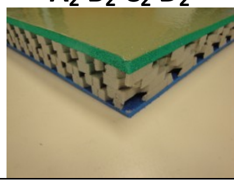
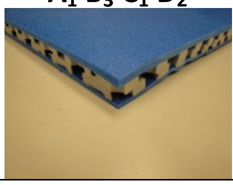
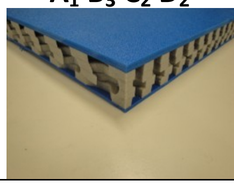
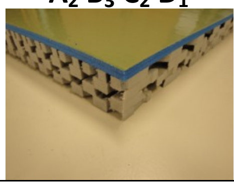
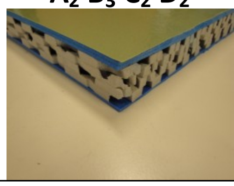
3.4.1 Further Results

This paragraph aims to show further results that are not included in "Paper C" thesis section. Referring to "Paper C – Materials and Methods", further specimen configurations were tested in addition to those ones named "architecture" and listed in Tab.3 (A,B,C,D,E,F,F,G) and according with the same impact testing procedure reported in paragraph 3.2. Following material and layer settings specifications are given as a backward step.

Specimens under test were structured by hot-melted layers overlapping. Each layer was made of the polymer foam "fully cross-linked Polyethylene closed cells" (PE). A typical sandwich structure was composed by a special varnish as covering, a top and bottom full layer that sustained a core cut layer section: depending on varnish application, top layer densities, core layer thickness and bottom layer presence, several configurations were available to test. In Tab. 3-8 previous material and layer settings are shown in term of factors (A,B,C,D) and levels (1,2,3), whose combinations identify several specimen configurations, listed in Tab. 3-9.

Factor		Level		
Type	**Name**	**1**	**2**	**3**
Covering	**A**	NO	Thick: Extra Thin Mat: Varnish Density: no	
Top layer	**B**	Thick: Normal Mat: PE Density: Low	Thick: Normal Mat: PE Density: Medium	Thick: Normal Mat: PE Density: High
Core Layer	**C**	CUT Thick:Normal Mat: PE Density: Low	CUT Thick: Thick Mat: PE Density: Low	
Bottom Layer	**D**	NO	Thick: Thin Mat: PE Density: High	

Tab. 3-8 Material and Layer Settings

$A_1 B_1 C_1 D_1$ 	$A_1 B_1 C_1 D_2$ 	$A_1 B_1 C_2 D_1$ 	$A_1 B_1 C_2 D_2$ 
$A_2 B_1 C_1 D_1$ 	$A_2 B_1 C_1 D_2$ 	$A_2 B_1 C_2 D_1$ 	$A_2 B_1 C_2 D_2$ 
$A_1 B_2 C_1 D_1$ 		$A_1 B_2 C_2 D_1$ 	$A_1 B_2 C_2 D_2$ 
$A_2 B_2 C_1 D_1$ 	$A_2 B_2 C_1 D_2$ 	$A_2 B_2 C_2 D_1$ 	$A_2 B_2 C_2 D_2$ 
$A_1 B_3 C_1 D_1$ 	$A_1 B_3 C_1 D_2$ 	$A_1 B_3 C_2 D_1$ 	$A_1 B_3 C_2 D_2$ 
$A_2 B_3 C_1 D_1$ 	$A_2 B_3 C_1 D_2$ 	$A_2 B_3 C_2 D_1$ 	$A_2 B_3 C_2 D_2$ 
Configuration Name Nomenclature: (1° FACTOR NAME)$_{\text{(1° LEVEL NAME)}}$ (2° FACTOR NAME)$_{\text{(2° LEVEL NAME)}}$ • • • (4° FACTOR NAME)$_{\text{(4° LEVEL NAME)}}$			

Tab. 3-9 Specimen Configurations

Impact tests were performed on all of configurations shown in Tab. 3-9, according both of procedures EN 913 and EN 1177 by using cylindrical and hemispherical missiles, respectively (besides in Paper C). In Fig. 3-3 and in Fig. 3-4, critical fall heights, equivalent heights and related acceleration peaks, respectively, are shown as comparisons. (refer to Appendix Tab. A-1 for EN913 values and to Appendix Tab A-2 for EN 1177 ones).

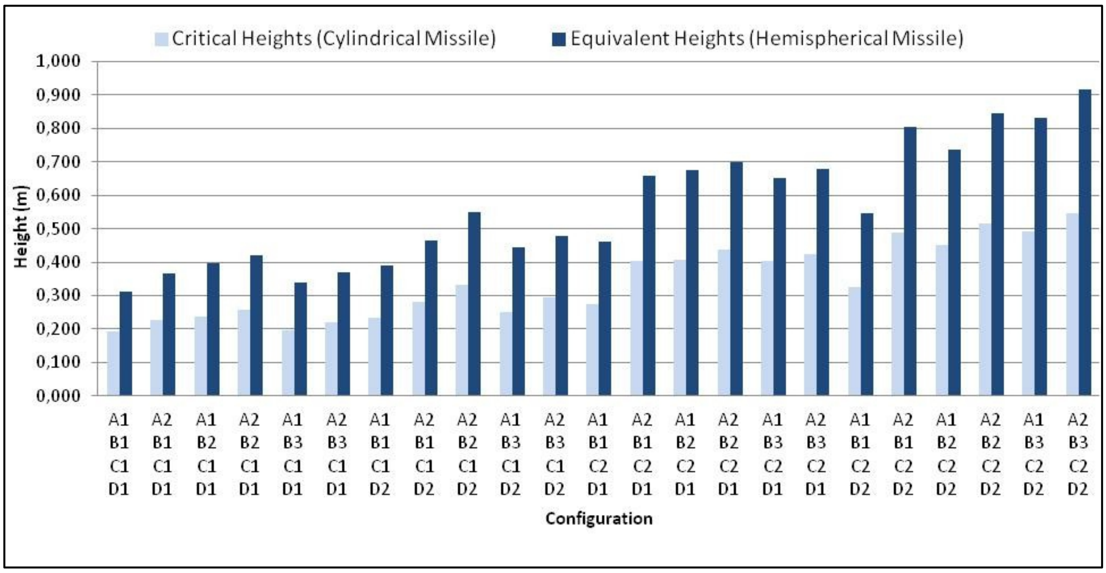


Fig. 3-3 Procedures Height Comparison

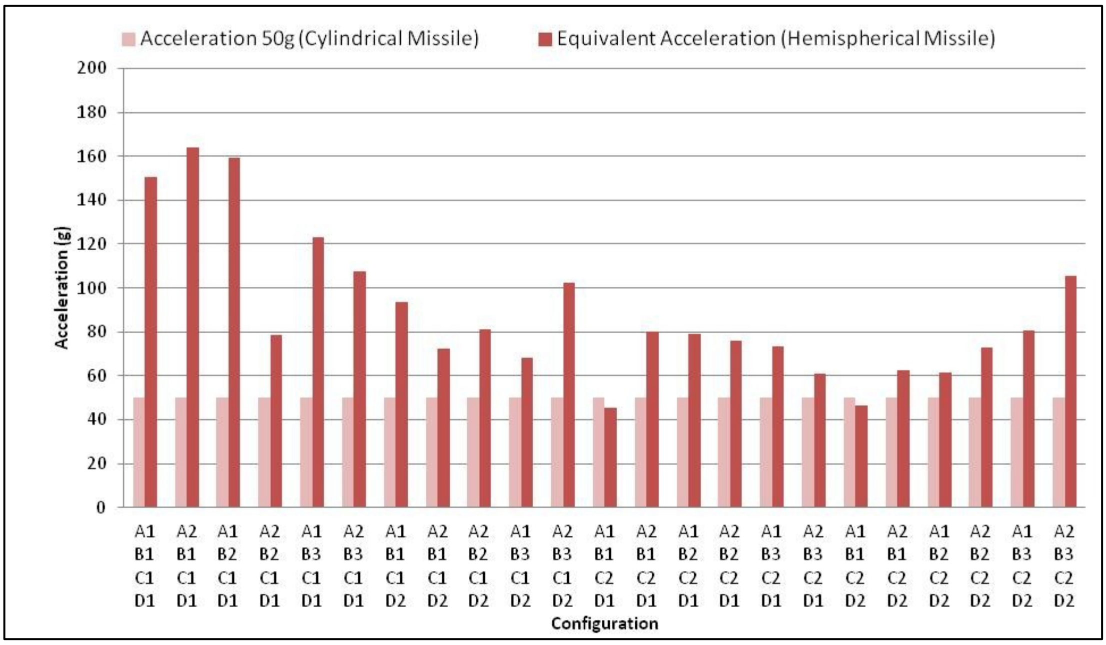


Fig. 3-4 Procedures Acceleration Peaks Comparison

As discussed in Paper C, equivalent heights appeared to be greater than Critical ones due to minor mass of the hemispherical missile compared with cylindrical one (also in this case). Equivalent acceleration peaks (Fig. 3-4) were greater than performance criterion of 50 g for all of specimens under study.

Following EN 1177 procedure, HIC values and AIS values (from level 1 to 6) , related to the equivalent drop heights shown before, were also evaluated by using formula (6) and (8) ("Biomechanics" paragraph 2.1.2) and filled in Appendix Tab A-2 and shown in Fig. 3-5.

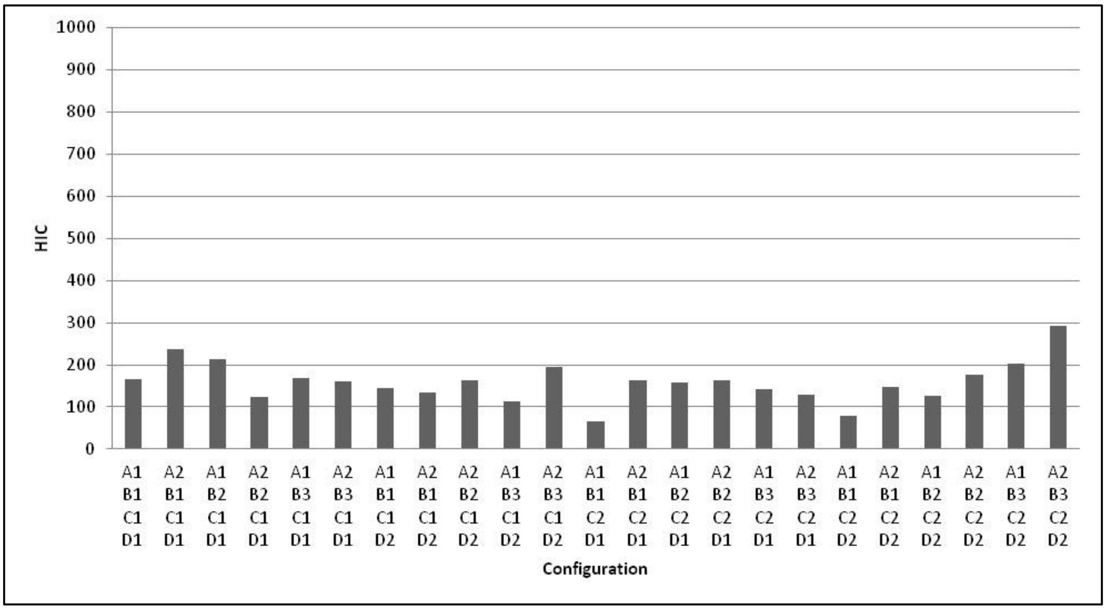


Fig. 3-5 HIC scores from equivalent drop heights

According to Abbreviated Injury Scale (AIS) definitions, each layer configuration has shown a probability not equal to zero percentage that minor brain injuries occurred (AIS1 values in Appendix Tab A-2). More severe injuries (from moderate to critical) appeared to be characterized by considerable probability from major drop heights (AIS2,3,4,5 scores in Appendix Tab A-2). Not significant probability that a fatal injury occurred was achieved for all of the configuration under test.

During a second experimental program phase, drop heights were arranged (by increasing) in order to comply the performance criterion of EN 1177 procedure by using the hemispherical missile and registering HIC and also related acceleration peaks values. In Fig. 3-6, HIC scores registered from drop heights that produced acceleration peaks of 200 g, are shown. (and filled in Appendix Tab A-3)

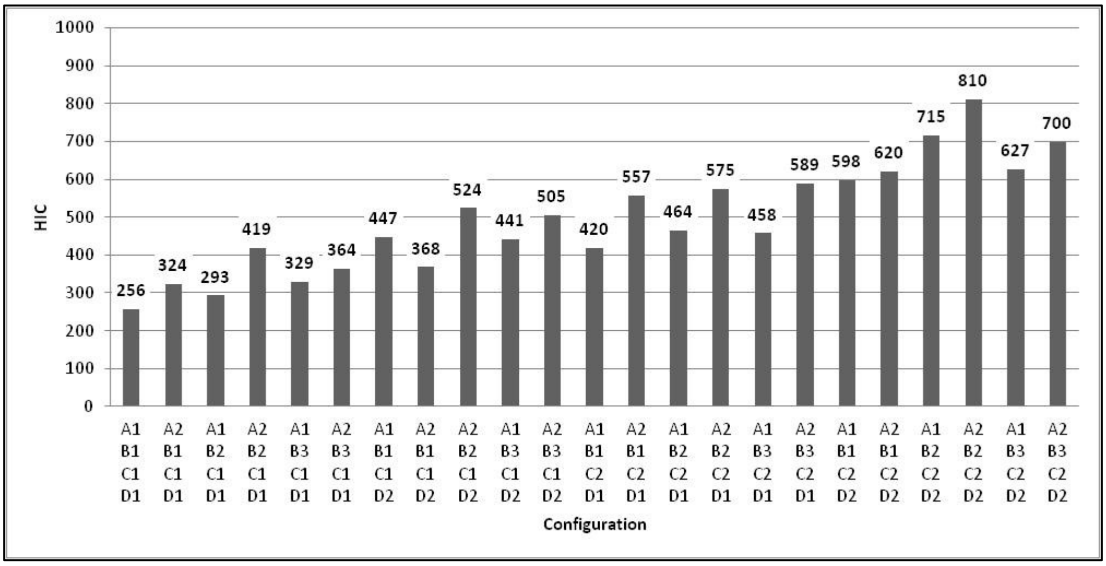


Fig. 3-6 HIC scores related to acceleration peaks ≈ 200g

No layer configuration met the performance criterion of HIC=1000 (showing considerable difference between evaluated HIC scores and the criterion of 1000 in Fig. 3-6) when the acceleration peaks achieved a maximum value of 200g.

Furthermore, measured velocity values before impacts were always lesser than the theoretical ones and, due to friction influence in the guidance system, theoretical drop heights were calculated and compared to measured ones, as in Fig. 3-7.

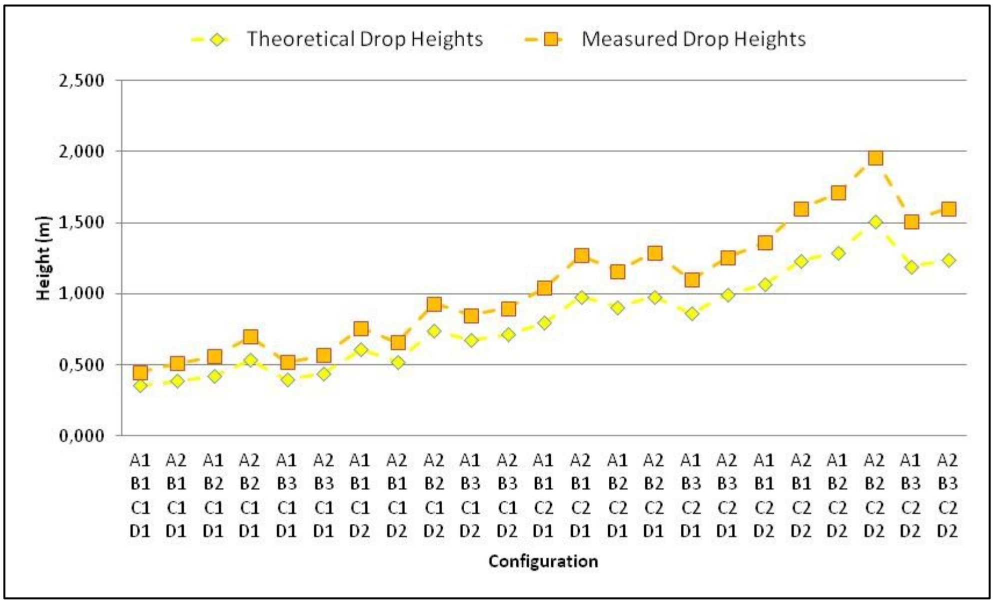


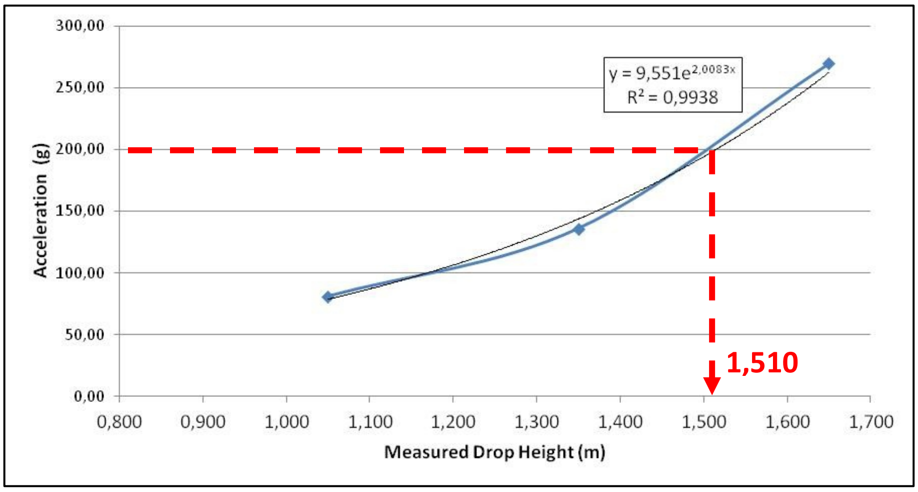
Fig. 3-7 Measured and Theoretical Drop Heights Comparison

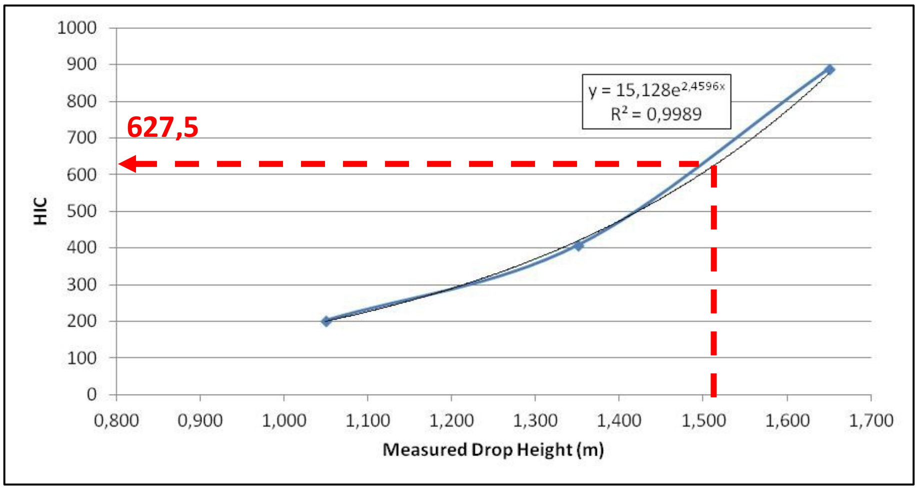
The numerical procedure, synthetically shown in "Paper C – Results", it has been implemented in order to simulate impact testing outcomes through real experimental data curve fitting process. A more detailed framework is shown, as follows:

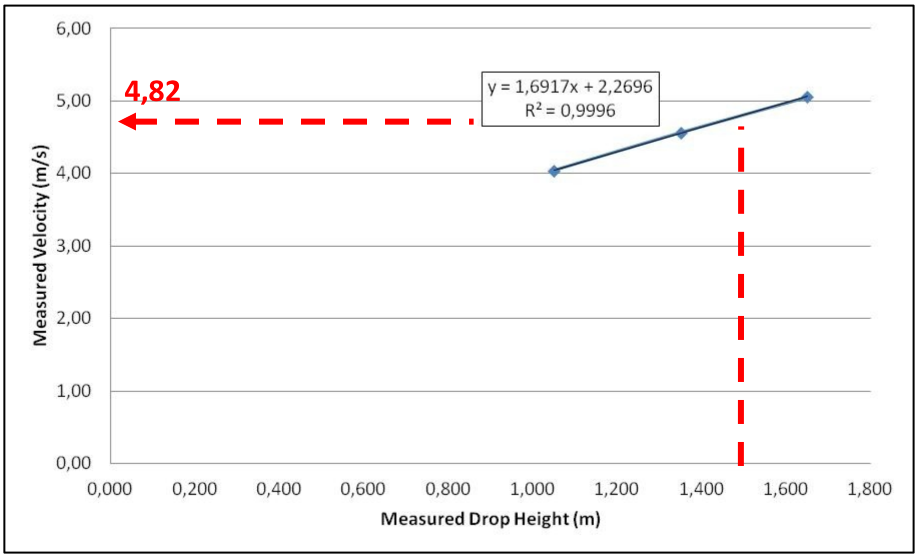
1. Starting from three collected (real) impact testing trial series (pilot experiments in following table) in terms of measured and theoretical drop height, measured impact velocity, acceleration peak, HIC,

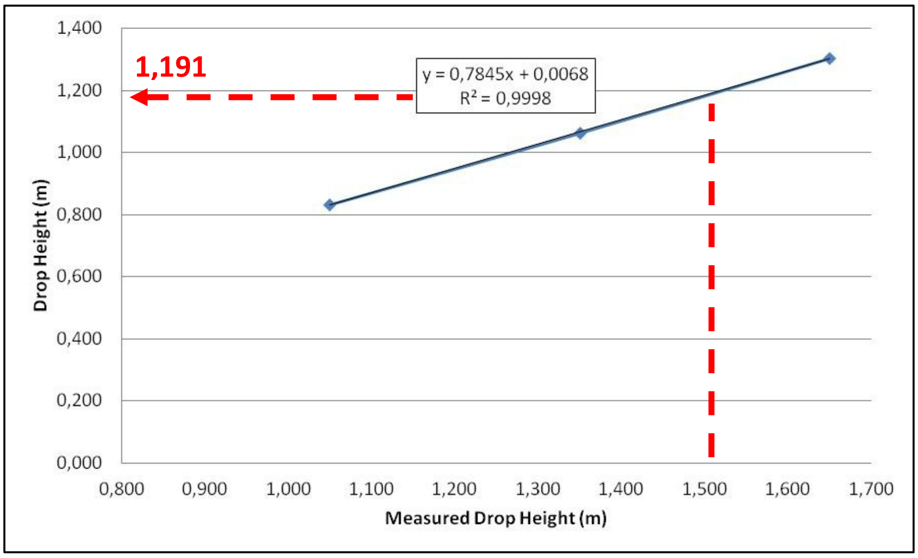
Pilot Experiments - Increasing Drop Heights			
	Pilot1	Pilot2	Pilot3
Measured Drop Height (m) - h_m	1,050	1,350	1,650
Theorethical Drop Eight (m) - h_{th}	0,832	1,063	1,303
Measured Velocity (m/s) - v_{th}	4,04	4,57	5,06
Measured Acceleration (g) - a_m	80,87	136,06	269,83
HIC	203	407	888

2. a fourth data series (Pilot 4) was simulated by fitting last three real scores with exponential functions and by using exponential formula in order to meet the acceleration performance criterion of 200g (referring to acceleration and HIC vs measured Drop Height plot; linear function and linear formula referring to measured velocity and theoretical drop height vs measured drop height plot).









3. By using these last outcomes (Pilot 4), a further impact testing series was carried out (confirmation experiment) in order to compare simulated and real

data in terms of percentage variation. This procedure was re-implemented until a small difference between the nominal value (as required in standards) of 200g and the acceleration value of the last confirmation experiment was achieved.

Curve Fitting Pilot Data (Pilot 4)		Confirmation Experiment	Percentage Variation
Measured Drop Height (m)	1,510	1,510	
Theoretical Drop Height (m)	1,191	1,194	-0,26%
Measured Velocity (m/s)	4,82	4,84	-0,33%
Measured Acceleration (g)	200	204,81	-2,35%
HIC	627,5	655,5	-4,27%

In Appendix Tab. A-4, percentage variations between simulated and real scores are given for all of configurations under study.

Finally, referring to Tab. 3-8 where were represented factors and levels whose combinations identified all of the configurations shown in Tab. 3-9, let's suppose to evaluate the joint effect of the factors on a response(i.e., critical fall height). A typical process is given by Pareto-Anova analysis [3],[4],[5] where the effect of a factor is defined to be change in response produced by a change in the level of the factor, frequently called "main effect". In Tab. 3-10 a 2^3x3^1 (24 treatments) factorial design is shown and critical fall heights has been chosen as response.

Treatments Number	Factor				Response
	A	B	C	D	Critical Fall Height (m)
1	1	1	1	1	0,358
2	2	1	1	1	0,387
3	1	2	1	1	0,423
4	2	2	1	1	0,535
5	1	3	1	1	0,395
6	2	3	1	1	0,441
7	1	1	1	2	0,525
8	2	1	1	2	0,609
9	2	2	1	1	

10	2	2	1	2	0,744
11	1	3	1	2	0,676
12	2	3	1	2	0,717
13	1	1	2	1	0,796
14	2	1	2	1	0,980
15	1	2	2	1	0,906
16	2	2	2	1	0,983
17	1	3	2	1	0,863
18	2	3	2	1	0,998
19	1	1	2	2	1,067
20	2	1	2	2	1,234
21	1	2	2	2	1,290
22	2	2	2	2	1,512
23	1	3	2	2	1,194
24	2	3	2	2	1,237

Tab. 3-10 Factorial Design

Where the ninth treatment is not present due to material configuration unavailability. Through Pareto Anova chart is possible to evaluate each single factor contribution, as in following Tab. 3-11:

	Level	Factor				
		A	B	C	D	
Mean	1	0,772091	0,7445	0,528182	0,672083	
	2	0,86475	0,913286	1,088333	0,982273	
	3		0,815125			
Mean Square Difference		0,008586	0,043112	0,31377	0,096217	
Degrees of Freedom		1	2	1	1	
Main Squares (S/g)		0,008586	0,021556	0,31377	0,096217	0,440129
Contribution Ratio (%)		2	5	71	22	

Tab. 3-11 Pareto-Anova Chart

This simple analysis has shown how the factor “C – Core Layer” contributes on the response “Critical fall Height” with the higher amount of 71%. Also the factor “D – Down Layer” reached a significant percentage (22%) while “Covering” and “Top Layer” seemed to have no influence in the analysis and it should be possible to reserve raw materials when configurations are being to be manufactured. The averages for each factor at its level (“Mean” line in Tab. 3-11) are also shown graphically in Fig. 3-8 , where the overall treatments average is also shown with a red line: they are separate effects of each factor and are commonly called *main effects.*

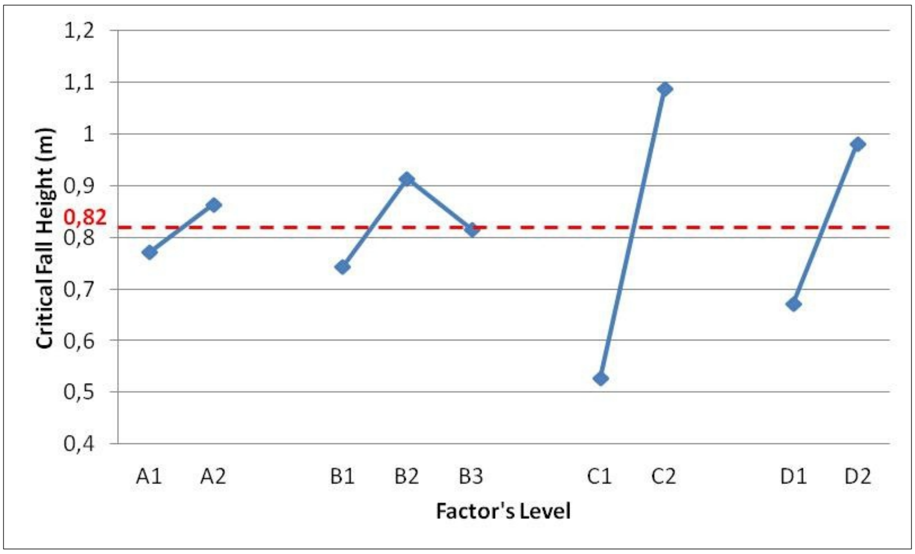


Fig. 3-8 Plots of factor effects

In Fig. 3-9 the effects of factor D when factor C is at level 1 and 2 are shown in the so called “Interaction Plot”:

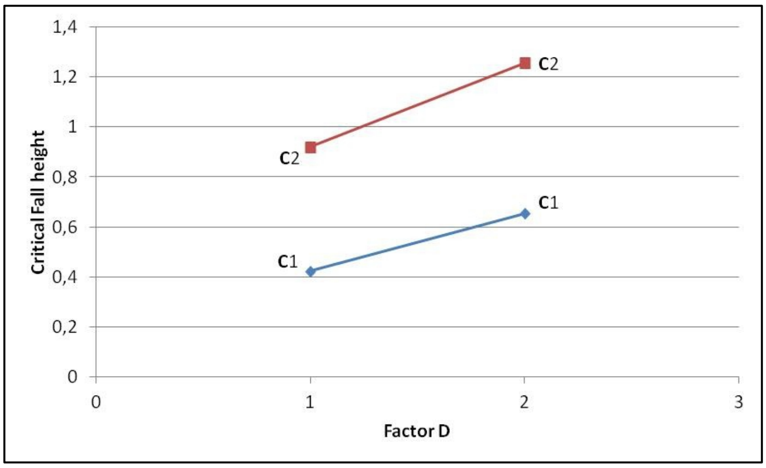


Fig. 3-9 Interaction Plot D-Factor Effect

Note that C1 and C2 lines are approximately parallel, indicating a lack of interaction between factors C and D. Both level 2 of factor C and D, in fact, define specimen configurations with higher thickness than respective levels 1 and, as a result, related performances (in term of critical fall height) simultaneously increase. In general, it has been confirmed that thickness magnitude is the first parameter to consider when a sandwich configuration is being to be designed.

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[2] A.S. McIntosh, P . McCrory, J. Comerford, "The dynamics head impacts in rugby and Australian rules football", in Medicine and Science - Sports and Exercise, 32(12), pp. 1980-1984, 2000

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4.
Further Developments and Conclusion

Further Developments

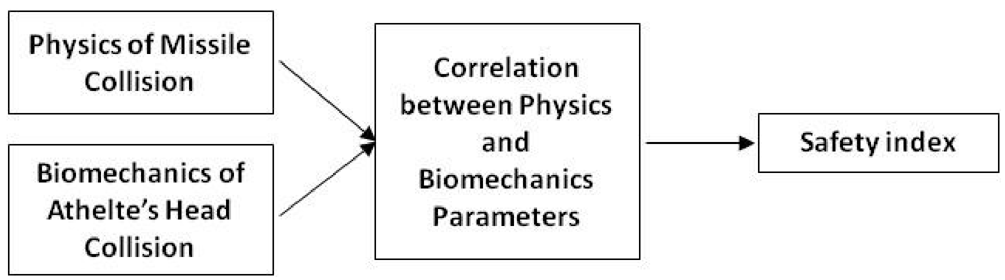
Previous experimental program phases have shown special impact testing procedures useful to characterize protective polymer-based foam devices from passive safety point of view. International Sports area Standards were adopted in order to build a special impact testing apparatus and to perform impact tests: results achieved were analyzed and discussed especially considering biomechanical research efforts on dynamics of head collisions.

In Experimental Program Phase 3, downline of EN 913 and EN 1177 impact testing results comparison, due to a lack of performance criterion specifications in term of acceleration peak (EN 1177), an underestimation of head injury risks was underlined. On the other hand, due to established brain trauma degree (through calculated AIS scores) in correspondence of EN 913 acceleration performance criterion of 50 g, critical fall heights were suggested to be certified by HIC performance parameter evaluation through impact tests with a hemispherical missile. Finally, in order to optimize protective devices choices by sports area technicians, a critical fall height of use were suggested to be established (i.e., for each sport disciplines, by defining maximum amount of impact energies which could be experienced by athletes during sport practice). Definitively, a joint monitoring on the acceleration peak, HIC and fall height parameters was well-recommended to be implemented in impact testing programs on protective devices. In Experimental Program Phase 2, a proposal of safety index formulation it has been shown in order to suggest a unequivocal method in selecting protective devices to be applied in sports area through a joint monitoring of impact characteristic parameters. Due to a scant series of impact testing data and due to accuracy of the model mathematics that has to be confirmed, a development of the proposed index it is recommended to be effected, for example, by evaluating proper K-indexes interval and assigned point with biomechanical analysis on real data of athletes collisions.

To this end, a new safety index formulation "S", functionally related to "HIC", acceleration peak "G_{max}" and critical fall height of use "h_u", it ought to be defined,

$$S = f(HIC, G_{max}, h_u)$$

and performance criterions in term of head injury risk, maximum amount of acceptable brain injury acceleration peak and frequently fall height in sports practice, it ought to be researched in real conditions of use. A special framework is shown in order to suggest the way to reach these latter aims.



In Experimental Program Phase 2, sandwich design parameter, in term of "covering", "top, core and bottom layer", influences on the response "critical fall height" were investigated by percentage variations calculation when these latter were present and not in several polymer-based configurations. A typical sandwich structure was finally suggested to be adopted by choosing one thin covering, one top layer (full) that overlapped a smooth core made of irregular layers and one bottom layer (full). Furthermore, in experimental program phase 3, a huge number of material configurations, available in four different thickness levels and manufactured by following previous design solutions, were tested and performances, in term of critical fall height, registered. In order to evaluate main effects of design factors (covering presence, top layer density, core layer thickness, bottom layer presence), a Pareto analysis was implemented and a factorial design built for all of the treatments under study. As a result, the thickness represented the major contribution parameter.

From product continuous improvement point of view, a new factorial design ought to be built by fixing, for example, the number of layers (at least 6 as suggested in previous study) and by assuming “covering thickness”, “core layer density” and “bottom layer density” as design factors. Top layer should be fixed as a full layer of normal thickness and medium density (due to its high performances shown in Fig. 3-3 and referring to all of thickness levels) made of cross-linked polyethylene closed cell foam. Covering should made of the special varnish introduced in experimental program phase 3 and core and bottom layer made of the same polyethylene closed cell foam. Therefore, an Analysis of Variance on this new 3^3 factorial design could be implemented and main factor effects could be investigated. An example of these 3 factors at 3 levels settings is shown as follow (for all of the suggested level magnitudes it has been verified that it should be possible to manufacture them through actual technologies on polymer-based foam processes):

FACTOR		**LEVEL**		
		1	2	3
“Covering Thickness”	A	extra thin	thin	normal
“Core Layer Density”	B	low	medium	high
“Bottom Layer Density”	C	low	medium	high

<u>Conclusion</u>

This thesis project aimed to characterize impact attenuation properties of sports protective devices and useful to protect athletes, during their practice, in case of potential accidents and, thus, to prevent consequences of brain concussions in case of head collision. Sports injuries statistics were widely examined: falls and related head impacts were underlined as the most dangerous ways to concuss. Head Injury Models, in Biomechanical scientific efforts, were studied in order extract indexes capable to measure brain injury thresholds and brain trauma degree. It has been paid also attention on Several International sports safety standards in order to comprehend impact testing procedures, and impact testing apparatus specifications assumed to characterize shock absorption properties of protective materials in use in sports area. Furthermore, Eco-design principles were studied in order to minimize consumptions and emissions in a product life-cycle vision. A flexible impact testing apparatus was built in Chemnitz University of Technology and capable to perform tests according several standard procedures: ASTM F1292, EN 913 and EN 1177. Three different experimental programs were followed and a huge number of polymer-based foam protective devices were characterized from impact attenuation properties point of view. Referring to principles of performances and product continuous improvement, a proper evaluation of design parameters was also implemented through Robust Design methods. Each experimental program aimed to adopt different standard procedures and to compare related results by performing impact tests on the available specimen configurations: several lacks were revealed in standard specifications and possible solutions have to be referred to the main goals achieved during the experimental programs, as follow:

- To improve the repeatability properties of the tests and the fair comparison of results collected using different testing laboratories, a fixed tolerance on measured/theoretical velocity ratio and declared percentage variation between the measured acceleration peak and the required performance criterion, it is recommended to be given. The same fixed tolerance is also well-recommended for ensure a proper evaluation of the critical condition of impacts.
- In correspondence of the EN 913 procedure critical fall heights, not equal to zero brain injury probabilities were registered, when impact tests were performed from equivalent drop heights, through the EN 1177 procedure and brain trauma degree evaluation algorithm. Therefore, other results achieved through the EN 1177 procedure have shown brain injury risks

underestimation due to a not proper performance criterion concerns. For this reason, a joint monitoring of acceleration peak, drop height and Head Injury Criterion (HIC) parameters, it is required to be effected.

- The ASTM F1292 apparatus units technical requirements ensured friction influences evaluation in the guidance system, hemispherical missile specifications compliance with ergonomics and accuracy of the registered parameters signals.
- From product design point of view, through applications of eco-design principles and Robust Design methods, it has been possible to select special polymer-based architectures that minimized environmental impacts and maximized performances in term of shock absorption, respectively.

To sum up, these studies have shown the necessity of additional specifications in EN 913 procedure in order to receive reliable and reproducible data. In addition, it has been shown how the severity of head collision were underestimate when a non-ergonomic missile was adopted. On the other hand, EN 1177 procedure seemed to fail in evaluating head injury potentials and a proper testing procedure is needed to be implemented by a joint monitoring on the characteristic parameters of impacts. Finally, International standard actually adopted in sports area don't provide a unequivocal method for assessing safety degree of protective devices but they just specify their conformity of use: a new impact testing protocol it is well-recommended to be introduced by starting, for example, from the main results achieved during this thesis project. This could be helpful to sports area technicians and responsible in making right decisions on proper impact attenuation properties evaluation of the protective devices and their consequent selection.

Appendix A

Var.	$A_1 B_1$ $C_1 D_1$	$A_2 B_1$ $C_1 D_1$	$A_1 B_2$ $C_1 D_1$	$A_2 B_2$ $C_1 D_1$	$A_1 B_3$ $C_1 D_1$	$A_2 B_3$ $C_1 D_1$	$A_1 B_1$ $C_1 D_2$	$A_2 B_1$ $C_1 D_2$	$A_2 B_2$ $C_1 D_2$	$A_1 B_3$ $C_1 D_2$	$A_2 B_3$ $C_1 D_2$	$A_1 B_1$ $C_2 D_1$	$A_2 B_1$ $C_2 D_1$	$A_1 B_2$ $C_2 D_1$	$A_2 B_2$ $C_2 D_1$	$A_1 B_3$ $C_2 D_1$	$A_2 B_3$ $C_2 D_1$	$A_1 B_1$ $C_2 D_2$	$A_2 B_1$ $C_2 D_2$	$A_1 B_2$ $C_2 D_2$	$A_2 B_2$ $C_2 D_2$	$A_1 B_3$ $C_2 D_2$	$A_2 B_3$ $C_2 D_2$
hm (m)	**0.240**	**0,280**	**0,300**	**0,320**	**0,260**	**0,280**	**0,290**	**0,350**	**0,410**	**0,330**	**0,360**	**0,340**	**0,490**	**0,500**	**0,540**	**0,490**	**0,510**	**0,400**	**0,610**	**0,560**	**0,640**	**0,610**	**0,680**
vm (m/s)	**1.95**	**2,11**	**2,15**	**2,25**	**1,97**	**2,07**	**2,15**	**2,35**	**2,55**	**2,22**	**2,41**	**2,32**	**2,81**	**2,83**	**2,93**	**2,81**	**2,88**	**2,52**	**3,10**	**2,98**	**3,18**	**3,11**	**3,28**
am (g)	**47.25**	**47,88**	**48,38**	**47,08**	**46,42**	**49,96**	**49,71**	**47,27**	**49,70**	**42,26**	**48,90**	**47,15**	**49,69**	**44,18**	**47,15**	**44,10**	**47,03**	**49,20**	**50,51**	**48,68**	**48,84**	**50,62**	**45,84**
hth (m) = hcr	**0.193**	**0,227**	**0,236**	**0,259**	**0,197**	**0,219**	**0,235**	**0,282**	**0,332**	**0,252**	**0,295**	**0,274**	**0,404**	**0,407**	**0,439**	**0,403**	**0,423**	**0,324**	**0,490**	**0,452**	**0,517**	**0,493**	**0,547**
vth (m/s)	**2.17**	**2,34**	**2,43**	**2,51**	**2,26**	**2,34**	**2,38**	**2,62**	**2,84**	**2,54**	**2,66**	**2,58**	**3,10**	**3,13**	**3,25**	**3,10**	**3,16**	**2,80**	**3,46**	**3,31**	**3,54**	**3,46**	**3,65**
rv	**0.897**	**0,900**	**0,888**	**0,899**	**0,871**	**0,885**	**0,900**	**0,898**	**0,899**	**0,874**	**0,906**	**0,898**	**0,908**	**0,903**	**0,901**	**0,906**	**0,911**	**0,900**	**0,896**	**0,898**	**0,899**	**0,899**	**0,897**

Tab. A-1 Impact testing Critical Parameters obtained by performing EN 913 procedure (all configurations)

Var.	$A_1 B_1$ $C_1 D_1$	$A_2 B_1$ $C_1 D_1$	$A_1 B_2$ $C_1 D_1$	$A_2 B_2$ $C_1 D_1$	$A_1 B_3$ $C_1 D_1$	$A_2 B_3$ $C_1 D_1$	$A_1 B_1$ $C_1 D_2$	$A_2 B_1$ $C_1 D_2$	$A_2 B_2$ $C_1 D_2$	$A_1 B_3$ $C_1 D_2$	$A_2 B_3$ $C_1 D_2$	$A_1 B_1$ $C_2 D_1$	$A_2 B_1$ $C_2 D_1$	$A_1 B_2$ $C_2 D_1$	$A_2 B_2$ $C_2 D_1$	$A_1 B_3$ $C_2 D_1$	$A_2 B_3$ $C_2 D_1$	$A_1 B_1$ $C_2 D_2$	$A_2 B_1$ $C_2 D_2$	$A_1 B_2$ $C_2 D_2$	$A_2 B_2$ $C_2 D_2$	$A_1 B_3$ $C_2 D_2$	$A_2 B_3$ $C_2 D_2$
hm (m)	**0,410**	**0,480**	**0,520**	**0,550**	**0,450**	**0,480**	**0,500**	**0,600**	**0,710**	**0,570**	**0,620**	**0,590**	**0,850**	**0,880**	**0,930**	**0,850**	**0,880**	**0,690**	**1,050**	**0,970**	**1,110**	**1,050**	**1,170**
vm (m/s)	**2,47**	**2,68**	**2,79**	**2,87**	**2,58**	**2,69**	**2,77**	**3,02**	**3,28**	**2,95**	**3,07**	**3,01**	**3,59**	**3,64**	**3,71**	**3,57**	**3,65**	**3,28**	**3,97**	**3,81**	**4,07**	**4,04**	**4,24**
am (g)	**150,3**	**164,1**	**159,4**	**78,6**	**123,3**	**107,4**	**93,6**	**72,4**	**81,2**	**68,2**	**102,2**	**45,5**	**80,2**	**79,2**	**76,2**	**73,3**	**60,9**	**46,7**	**62,5**	**61,6**	**72,7**	**80,9**	**105,5**
HIC	**165**	**236**	**213**	**123**	**170**	**161**	**144**	**133**	**163**	**113**	**195**	**66**	**162**	**158**	**164**	**143**	**128**	**79**	**146**	**127**	**178**	**203**	**291**
hth (m) = hcr	**0,311**	**0,366**	**0,397**	**0,419**	**0,339**	**0,369**	**0,391**	**0,465**	**0,549**	**0,444**	**0,479**	**0,462**	**0,657**	**0,676**	**0,700**	**0,650**	**0,677**	**0,547**	**0,804**	**0,738**	**0,845**	**0,832**	**0,917**
vth (m/s)	**2,84**	**3,07**	**3,19**	**3,28**	**2,97**	**3,07**	**3,13**	**3,43**	**3,73**	**3,34**	**3,49**	**3,40**	**4,08**	**4,15**	**4,27**	**4,08**	**4,15**	**3,68**	**4,54**	**4,36**	**4,67**	**4,54**	**4,79**
rv	**0,871**	**0,873**	**0,874**	**0,872**	**0,868**	**0,877**	**0,885**	**0,880**	**0,879**	**0,882**	**0,879**	**0,885**	**0,879**	**0,876**	**0,868**	**0,874**	**0,877**	**0,890**	**0,875**	**0,872**	**0,872**	**0,890**	**0,885**
AIS1 (%)	**15,53**	**29,45**	**24,87**	**8,42**	**16,27**	**14,62**	**10,00**	**11,66**	**15,17**	**6,78**	**21,25**	**1,49**	**14,99**	**14,27**	**15,35**	**11,49**	**9,20**	**2,67**	**12,17**	**9,04**	**17,76**	**22,84**	**41,25**
AIS2 (%)	**5,13**	**9,85**	**8,25**	**2,82**	**5,37**	**4,83**	**3,33**	**3,87**	**5,01**	**2,29**	**7,02**	**0,52**	**4,95**	**4,72**	**5,07**	**3,81**	**3,07**	**0,92**	**4,04**	**3,02**	**5,86**	**7,55**	**14,35**
AIS3 (%)	**1,80**	**3,31**	**2,81**	**1,02**	**1,88**	**1,70**	**1,20**	**1,38**	**1,76**	**0,83**	**2,41**	**0,20**	**1,74**	**1,66**	**1,78**	**1,36**	**1,11**	**0,35**	**1,43**	**1,09**	**2,04**	**2,59**	**4,71**
AIS4 (%)	**0,39**	**0,72**	**0,61**	**0,22**	**0,41**	**0,37**	**0,26**	**0,30**	**0,38**	**0,18**	**0,52**	**0,04**	**0,38**	**0,36**	**0,39**	**0,29**	**0,24**	**0,08**	**0,31**	**0,24**	**0,44**	**0,56**	**1,02**
AIS5 (%)	**0,02**	**0,05**	**0,04**	**0,01**	**0,03**	**0,02**	**0,02**	**0,02**	**0,02**	**0,01**	**0,03**	**0,00**	**0,02**	**0,02**	**0,02**	**0,02**	**0,01**	**0,00**	**0,02**	**0,01**	**0,03**	**0,04**	**0,07**
AIS6 (%)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**

Tab. A-2 Impact Testing parameters (equivalent to EN 913) obtained by performing EN 1177 procedure (all configurations)

Var.	$A_1 B_1$ $C_1 D_1$	$A_2 B_1$ $C_1 D_1$	$A_1 B_2$ $C_1 D_1$	$A_2 B_2$ $C_1 D_1$	$A_1 B_3$ $C_1 D_1$	$A_2 B_3$ $C_1 D_1$	$A_1 B_1$ $C_1 D_2$	$A_2 B_1$ $C_1 D_2$	$A_2 B_2$ $C_1 D_2$	$A_1 B_3$ $C_1 D_2$	$A_2 B_3$ $C_1 D_2$	$A_1 B_1$ $C_2 D_1$	$A_2 B_1$ $C_2 D_1$	$A_1 B_2$ $C_2 D_1$	$A_2 B_2$ $C_2 D_1$	$A_1 B_3$ $C_2 D_1$	$A_2 B_3$ $C_2 D_1$	$A_1 B_1$ $C_2 D_2$	$A_2 B_1$ $C_2 D_2$	$A_1 B_2$ $C_2 D_2$	$A_2 B_2$ $C_2 D_2$	$A_1 B_3$ $C_2 D_2$	$A_2 B_3$ $C_2 D_2$
hm (m)	0,450	0,510	0,560	0,700	0,520	0,570	0,660	0,760	0,930	0,850	0,900	1,040	1,270	1,160	1,290	1,100	1,260	1,360	1,600	1,710	1,960	1,510	1,600
vm (m/s)	2,65	2,76	2,88	3,24	2,79	2,94	3,21	3,46	3,82	3,64	3,75	3,95	4,39	4,22	4,39	4,12	4,43	4,58	4,92	5,03	5,45	4,84	4,93
am (g)	189,2	203,5	235,3	219,3	263,1	241,1	227,4	196,9	231,0	205,8	215,8	172,7	213,5	166,7	157,6	166,8	174,5	188,0	178,5	229,2	276,2	204,8	177,1
HIC	242	333	377	471	451	466	427	452	632	460	560	338	544	399	431	400	495	522	523	738	1019	656	621
hth (m) = hcr	0,358	0,387	0,423	0,535	0,395	0,441	0,525	0,609	0,744	0,676	0,717	0,796	0,980	0,906	0,983	0,863	0,998	1,067	1,234	1,290	1,512	1,194	1,237
vth (m/s)	2,97	3,16	3,31	3,71	3,19	3,34	3,60	3,86	4,27	4,08	4,20	4,52	4,99	4,77	5,03	4,64	4,97	5,16	5,60	5,79	6,20	5,44	5,60
rv	0,892	0,871	0,869	0,874	0,872	0,879	0,892	0,895	0,894	0,892	0,893	0,875	0,879	0,884	0,873	0,886	0,890	0,886	0,878	0,869	0,878	0,889	0,879

Tab. A-3 Impact Testing Critical Parameters (acceleration peaks ≤ 200g) obtained by performing EN1177 procedure

Perc. Varia tion	$A_1 B_1$ $C_1 D_1$	$A_2 B_1$ $C_1 D_1$	$A_1 B_2$ $C_1 D_1$	$A_2 B_2$ $C_1 D_1$	$A_1 B_3$ $C_1 D_1$	$A_2 B_3$ $C_1 D_1$	$A_1 B_1$ $C_1 D_2$	$A_2 B_1$ $C_1 D_2$	$A_2 B_2$ $C_1 D_2$	$A_1 B_3$ $C_1 D_2$	$A_2 B_3$ $C_1 D_2$	$A_1 B_1$ $C_2 D_1$	$A_2 B_1$ $C_2 D_1$	$A_1 B_2$ $C_2 D_1$	$A_2 B_2$ $C_2 D_1$	$A_1 B_3$ $C_2 D_1$	$A_2 B_3$ $C_2 D_1$	$A_1 B_1$ $C_2 D_2$	$A_2 B_1$ $C_2 D_2$	$A_1 B_2$ $C_2 D_2$	$A_2 B_2$ $C_2 D_2$	$A_1 B_3$ $C_2 D_2$	$A_2 B_3$ $C_2 D_2$
Δa_m (%)	+5,70	-1.73	-15.0	-8.79	-23.9	-17.0	-12.0	-1.58	-13.4	-2.81	-7.33	+15.8	-6.3	+20	+26.9	+19.9	+14.6	+6.37	+12.1	-12.7	-27.5	-2.35	+12.9
ΔHIC (%)	+5,86	-2.43	-22.2	-10.9	-26.9	-21.7	-13.6	-1.12	-17.1	-3.93	-9.84	+24.3	+2.51	+16.2	+33.3	+14.5	+19.1	+14.5	+18.6	-3.08	-20.4	-4.27	+12.6

Tab. A-4 Percentage Variations between simulated and real scores in term of acceleration peaks and HIC

Paper A

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Enhancing Impact Testing of Protective Polymer-based Foams According to EN 913 for Application in Sports Area

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Abstract

This paper shows preliminary results of a research aimed to improve passive safety of gymnastic equipments. To assess the impact attenuation performances of protective devices, mainly realized with polymer-based foams, impact testing standards are applied. Due to lack of criticism about test procedures and analysis of experimental results, the choice of the most safe device is not trivial. The first part of the paper shows the main impact testing procedures provided by international standards and defined for gymnastic equipments and playground area. In accordance to these standards the main impact attenuation performances for passive safety assessment are defined. The second part of the paper shows first experimental results obtained using new testing apparatus developed at the Sports Equipment and Technology Lab of Chemnitz University of Technology. Impact attenuation performances of two protective devices realised with polymer-based foams are analysed. The parameter of theoretical drop height is introduced to compare experimental results collected in our laboratory with others previously collected in an accredited laboratory. The comparison of test standards reveals lack of specifications in EN 913, that should be modified. Finally, sources of uncertainty and reasons of unfair comparison are discussed in order to advice managers and technicians about the consequences of their choices in evaluating performances of passive safety devices for gymnastic equipment.

1 Introduction

Safety is one of the mostly expected functional requirements in designing sports equipment to be used in both organized sport activities (e.g. elite, professional) and not organized ones (e.g. leisure, home). To minimize injury risk during exercises or competitions related to events like accidental falls, entrapments or impacts during athletic performance, there are several devices and materials with a single purpose: Protection. Thus, there is a need to quantify the protective level of those devices used in gymnastics, indoor and outdoor playground areas, martial arts, alpine skiing and many others. International standards provide specific recommendations and rules in order to standardize the testing procedures of protective equipment such as helmets [1], wall padding [2] or floor mats [3].

A report [4] on injuries in the European Union has estimated an amount of 7000/year fatal sport injuries. Further, non-fatal injuries related to physical activities and sport counted 5.8 million/year events (1.3 million of whom involves children under the age of 15). Team-ball sports accounted for about 40% of all hospital treated sport injuries and the head was the most critical body part involved in falls mode accidents.

In the same manner, recent studies centred on head injury risk [5] have estimated that in the USA nearly 220.000/year children ages 14 and under were treated in emergency departments for injuries associated with playground equipment, the majority (57%) of whom were placed in schools or parks. Falls were the most common mode of playground injury that involved seriously child's head. A 2002 survey has found that a lot of public playgrounds lacked adequate protective surfacing, the most critical safety factor on playgrounds together with adult supervision. Because of these accidents playground equipment and playing surface systems testing standards have been developed by American Society for Testing Materials (ASTM) in order to markedly reduce head injury risk to children by using protective surfaces onto and around the playground such as energy-absorbing materials (plastic, rubber, wood). One of these specifications, named ASTM F1292:2004 [6], describes impact attenuation performance requirements for playground surfaces and surfacing materials and provides a means of determining impact attenuation performance using a test method that simulates the impact of a child's head with the surface. The second one, ASTM F355:2001 [7], is centred on measurement of certain shock-absorbing characteristics, the impact force-time relationships, and the rebound properties of playing surface systems.

In the same manner, several European standards referring to safety of sports area could be found, such as those approved by CEN (European Committee for Standardization): EN 913:2009 [8] specifies general safety requirements and test methods for all pieces of gymnastic equipment intended for use supervised by a competent person. Furthermore, EN 1177:2008 [9] determines the impact attenuation of playground surfaces.

Even if all of the described standards seems to be applied into different sports area fields, acceleration magnitude is most frequently investigated as well as the impact testing devices are similar.

The aim of this study was to investigate if the description given in EN 913 was sufficient to lead to comparable results in case of materials being tested by different laboratories and really useful to improve passive safety.

Therefore impact tests were performed on several protective surfaces made of polymer foams by means of impact testing device according to a European Standards procedure. Subsequently, a comparison of these test results with others carried out in a accredited laboratory is shown.

2 EN 913 and ASTM F 1292 Standards

Low-velocity impacts [10] are usually conducted using a drop-weight rig in order to measure the acceleration during impact. An example of this kind of testing device is shown in *Fig. 1*.

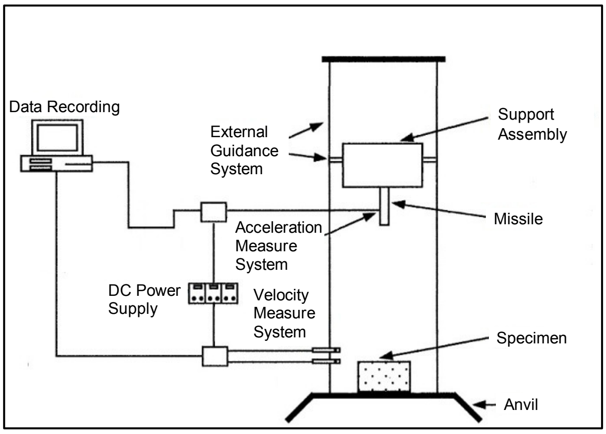


Fig. 1: General impact testing set-up

A missile is dropped onto the specimen from a predetermined drop height. The acceleration of the missile during the impact is measured using an accelerometer and associated data recording equipment. Impact velocity is also measured. The specimens tested are supported by a stiff steel substrate in order to limit the overall bending of the specimens. A typical simulation result is represented graphically as a profile of acceleration on impact (*g*) over a period of time (*t*) known as *g-time* trace (*Fig. 2*).

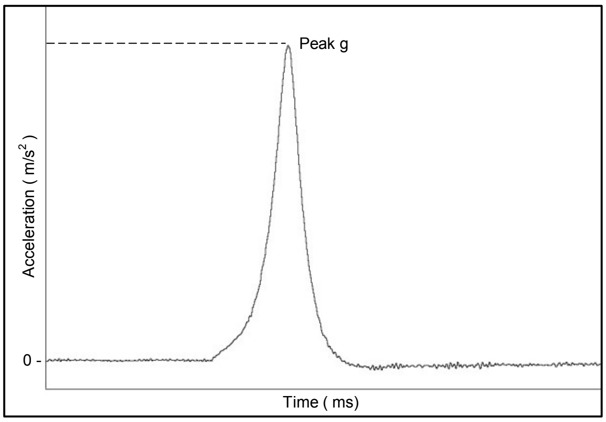


Fig. 2: Acceleration-Time Plot

The acceleration-time plot allows to quantify the consequences of the impact in terms of g-max or integral evaluation of the curve correlated to potential head injuries.

G-max is the measure of the maximum acceleration (shock) produced by an impact of the missile that falls due to gravity ($g = 9.806\ m/s^2$) onto the specimen.

In order to avoid injuries in case of frontal head impact, the threshold safety value is considered 50*g* that seems to be issued from *Wayne State Tolerance Curve* [11] .

On the other hand, many authors in the field of automotive or aerospace crash analysis suggest 200*g* as maximum tolerable threshold to avoid fatal consequence during a frontal head impact that takes more than 3ms.

The other index widely used and accepted as correlated to potential injuries is the *Head Injury Criterion* (HIC), based on the following expression:

$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} \quad (1)$$

Where

a(t) = acceleration at time *t*

$t_2 - t_1$ = is the time interval on the acceleration-time plot that maximize HIC trial scores. Reference values are widely shown in literature [12].

The Head Injury Criterion or HIC score is an empirical measure of impact severity based on published research describing the relationship between the magnitude and duration of impact accelerations and the risk of head trauma [13].

Several impact testing procedures have been implemented in order to characterize polymer-based foam (see, for example, [14]).

For the aim of this paper and for completeness of the protocol, the EN913 standard, concerning sport equipment, is compared with ASTM F1292 one, that concerns public sports area safety regulations.

2.1 UNI EN 913:2009 – Gymnastic equipment - General safety requirements and test methods

This European Standard specifies general safety requirements and test methods for all pieces of gymnastic equipment intended for use supervised by a competent person and not specified in other, individual standards. It is not applicable to other sports equipment, playground equipment, stationary training equipment or educational training equipment.

2.1.1 Summary of Test Method

EN 913 describes a shock absorption testing procedure where a striker is dropped onto the protective surface and the deceleration during the impact is monitored: first, the indenter is raised to the required height and locked into position and then is released to fall vertically onto the test piece (minimum dimensions of 500 x 500 mm). The acceleration of the indenter during the impact is measured using an accelerometer and recorded data are processed to obtain the peak deceleration during the impact. Five tests at the same location are carried out at intervals of between 1 min and 3 min. Shock absorbency measure is expressed as the mean value of peak acceleration values from the last three impacts that shall not exceed $500\ m/s^2$.

2.1.2 Test Apparatus

A list of requirements regarding the test apparatus components is given in the EN 913 document. Referring to the indenter (*Fig. 3*), it is defined to be made of metal and to have a cylindrical impacting surface with a total mass of 8±0.1 kg.

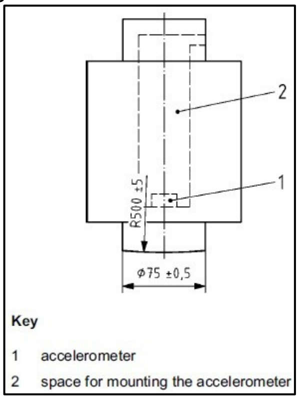


Fig. 3: EN 913 Missile [8]

2.2 ASTM F1292: 2009 – Standard Specification for Impact Attenuation of Surfacing Materials within the Use Zone of Playground Equipment

The ASTMS 1292 specifies impact attenuation performance requirements for playground surfaces and surfacing materials and provides a means of determining impact attenuation performance using a test method that simulates the impact of a child's head with the surface.

2.2.1 Scope

The test method quantifies impact in terms of g-max and *HIC* scores. The purpose of this specification is to reduce the frequency and severity of fall-related head injuries to children by establishing a uniform and reliable means of comparing and specifying the impact attenuation of playground surfaces.

2.2.2 Summary of Test Method

The impact attenuation of a playground surface or surfacing materials is measured using an impact test in which a missile is dropped onto the playground surface from a predetermined drop height. The acceleration of the missile during the impact is measured using an accelerometer and associated data recording equipment. The acceleration time history is analyzed to determine *g-max* and *HIC* scores. For each playground surface sample (minimum dimensions of 460 x 460 mm) at each reference temperature (6, 23, and 49°C) and drop height, scores from the second and third of three consecutive drops (interval of 1.5±0.5 min) are averaged to give average scores. The critical fall height is determined as the highest theoretical drop height from which the surface performance parameters meet the performance criterion: g-max score not exceeding 200 *g* and a *HIC* score not exceeding 1000. The theoretical drop height, *h*, is calculated from a measurement of impact velocity, *v*, using the eq. 2:

$$h = \frac{v^2}{2\,g} \quad (2)$$

where *g* is the acceleration due to gravity.

2.2.3 Test Apparatus

A list of required test apparatus components is given in the ASTM F1292 document: the latter provides brief specifications for each units displayed in *Fig. 1*. For example the missile must be made of Aluminum Alloy 6061-T6, finished with a surface roughness of 25 µm. The missile shall have a hemispherical impacting surface with an external diameter of 160±2 mm (*Fig. 4*). The total mass of the drop assembly, which is the combined mass of the missile, accelerometer, and supporting assembly is defined to be 4.6±0.02 kg.

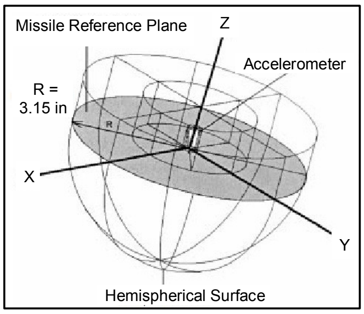


Fig. 4: ASTM Missile [6]

For a complete units specification list please refer to ASTM F1292 document.

2.3 Comparison of EN 913 and ASTM F1292

The standard test methods mentioned above aim to provide guidelines to quantify the shock attenuation properties of sports equipment protective devices through impacting a rigid body onto the specimen. In detail both of the standards use different protocols regarding i.e. the shape of the contact area of the missile, striking mass and evaluation parameters.

Furthermore, EN 913 lacks detailed information about important facts such as the way to fulfil requirements like to "allow the indenter to fall smoothly and vertically". The solution is presented by the ASTM F1292: a guidance system that offers one DOF movement of the drop assembly in vertical direction. In this manner potential friction has to be taken into account through an impact velocity analysis.

Furthermore, the test protocol strictly defined by ASTMF1292 is taken as best practice to update the specifications missing into the 913 protocol.

3 Experimental Program

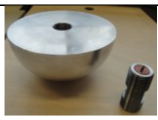
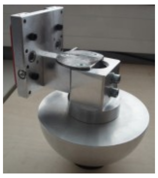
Scope of this study was to achieve shock absorption characterization on samples made of polymer foam through impact testing procedures following the protocol of EN 913. In the future of the project also testing according to ASTM F1292 is planned. Therefore an adaptable impact testing apparatus was built in laboratories of Chemnitz University of Technology that is capable to be used to perform testing according to both of the standards.

The experimental program began with a concept design approach where head striker inter-changeability was the main functional request taken into account. Afterwards, apparatus was manufactured following both American and European standard's specifications. Then the whole device was assembled to comply with the claims in EN 913 and additionally set-up following ASTM protocol recommendations on an impact velocity measurement system to quantify energy loss in guidance system due to friction issues.

Due to accredited laboratory impact tests execution on similar materials (specified in 3.2) through EN 913 standard protocol, a peculiar study centered on shock absorption of polymer foam following the same European standard protocol was implemented. Finally, the results obtained in this study were compared to those reported by an accredited laboratory.

3.1 Impact Testing Device

The following *Tab. 1* is intended to show components and specifications of the manufactured drop assembly.

EN 913	ASTM F1292
Missile	
	
Support Assembly	
	
Drop Assembly	
	
Material: Steel and Aluminum Required Mass: 8 ± 0.1 kg Measured Mass: 7991.25 g	Material: Aluminum 6061 Required Mass: 4.6 ± 0.02 kg Measured Mass: 4623.70 g

Tab. 1: Drop Assembly Components

It is relevant to point out that the whole apparatus is capable to perform impact tests according each of the two different protocol units specifications, simply by replacing the missile. Therefore, a special threaded shaft, shown in section “Missile” of *Tab. 1*, that contains accelerometer and cables, is characterized by a diameter that realizes both cylindrical and hemispherical missile mechanical coupling.

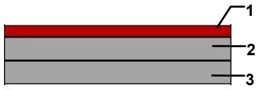
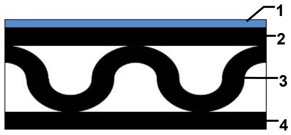
In *Fig. 5* whole installed test apparatus is shown. The drop assembly was mounted to a monorail linear guidance system (type HRW, THK Co. Ltd.). Drop height was controlled by an adjustable magnet mechanism.

Fig. 5: Fully Installed Test Apparatus

Impact velocity was measured by a ±40 mm laser displacement sensor (type LK-G152, Keyence Corp.) that worked as a light gate. Acceleration was detected by a ±500 g piezoelectric uniaxial transducer (type 8614A500M1, Kistler Holding AG) aligned with the cylinder vertical axis. All data recording and displaying was performed by a multi-channel measurement amplifier (type CS-7008, imc Messsysteme GmbH) at sampling frequencies of 20 kHz (accelerometer) and 100 kHz (laser). In order to prevent aliasing in the digitized acceleration data, the acceleration signals was filtered with a low-pass filter (corner frequency of half of the channel sampling rate).

3.2 Materials and Specimen

Experimental results were achieved carrying out several impact tests on two different sample configurations named Configuration A and Configuration B, both sections shown in *Tab. 2*: any polymer-based foam layers, 12 mm of thickness, are coupled in two different architectures through hot-melt process. Closed cell fully cross-linked Polyethylene (PE) foam with a density of 30 kg/m^3 manufactured by D&S S.r.l [15] was studied. Each specimen measured 500 mm in width and 500 mm in length.

Configuration A	Configuration B
	
1. Red PVC Coating 2. 1° Layer (upper) 3. 2° Layer (lower)	1. Blue PVC Coating 2. 1° Layer (upper) 3. 2° Layer (wave) 4. 3° Layer (lower)

Tab. 2: Configuration A,B Sections

3.3 Impact Testing Protocol

Low velocity impact tests were conducted using the drop-weight rig shown in *Fig. 5*.

The head of the striker (cylindrical missile shown in *Tab. 1*) was attached to a support assembly, both connected to a lifting carriage (guidance system) which raised the drop assembly to the desired height. At the required height, the whole drop assembly was uncoupled (through an electro-magnetic releasing device installed in the test rig) and fell under gravity by a vertical guidance system on the center of a sample that was fixed by double-sided adhesive on a steel plate (anvil) in order to limit the overall bending of the specimen. All test pieces were conditioned for a minimum of 3 h at the test temperature of 23±2 °C. The impact velocity was measured by a laser displacement sensors sited along the path of the striker, just above the specimen. Sequential interruption of the laser beam by a plate attached to the falling striker triggered the starting and stopping of a counter-timer. The impact velocity was determined from the elapsed time and the plate height.

In order to measure drop assembly deceleration, the testing rig was equipped with a piezoelectric accelerometer (rigidly mounted into the missile through a PE high density threaded shaft) connected to a data acquisition PC computer for post-processing acceleration as a function of time. An example of a yield acceleration-time trace is given in *Fig. 6*, evaluated on a foam specimen from 35 cm of height through a drop assembly of 8 kg equipped with a cylindrical head.

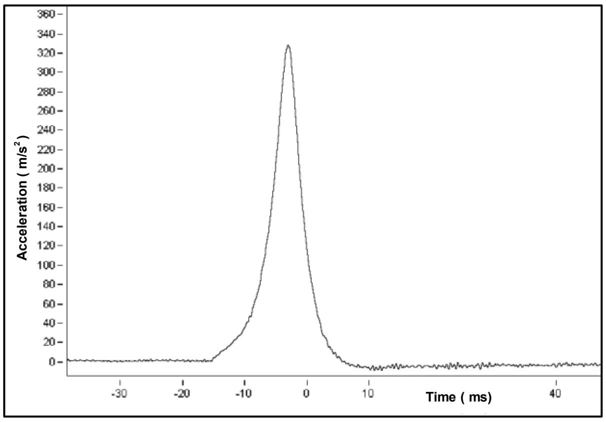


Fig. 6: Acceleration-Time Displayed

Every foam panel specimen under examination was subjected to five consecutive low velocity impacts, with an interval of 1.5 min. All acceleration-time traces were examined to ensure that it contained no spurious peaks. Furthermore, prior to the onset of impact, it was verified that the recorded acceleration value was 0±20 m/s^2 and the acceleration waveform descended from its maximum value to a stable value of 0±20 m/s^2 without overshooting the zero baseline by more than 20 m/s^2. This procedure also described in ASTM F1292 ensured that the recorded data were correct.

3.4 Data Processing

All recorded trials were analyzed in terms of the measured peak value of the acceleration (a_m), impact velocity (v_m) and the related drop height (h_m). On the other hand, the related theoretical velocity (v_{th}) respectively the related theoretical drop height (h_{th}) were calculated. More details about symbols adopted are given through a nomenclature sheet in *Tab. 3*

Variable	Description	Formula
h_m	is the drop height set up before impact event	
v_m	is the velocity measured by light gate device before impact event	
a_m	is the peak acceleration measured by transducer during impact event	
v_{th}	is the theoretical velocity that should be observed in a free-fall from the height h_m	$v_{th}=\sqrt{2*g*h_m}$ (3)
h_{th}	is the theoretical height related to the velocity v_m	$h_{th} = \frac{v_m^2}{2*g}$ (4)
r_v	is the ratio of measured and theoretical velocity	$r_v = \frac{v_m}{v_{th}}$ (5)

Tab. 3: Nomenclature – Symbols Adopted

4 Results

Impact tests were performed on two different sample configurations, named Configuration A and Configuration B during three series of tests. Drop height h_m was set to the value reported by the accredited laboratory ($h_{m,A}$=0.27 m; $h_{m,B}$=0.50 m) on test series 1 and test series 2. On test series 3, drop height was adjusted ($h_{m,A}$=0.21 m; $h_{m,B}$=0.35 m) in order to achieve a maximum acceleration of 500 m/s^2 as required in EN 913. Values of the last 3 on a series of 5 impacts were collected to calculate arithmetic mean and standard deviation for each configuration and testing condition.

The results displayed in *Tab. 4* and *Tab. 6: Results for specimen Config. B,*show a significantly higher impact velocity during the tests conducted at Chemnitz University of Technology on test series 1 and 2 compared to the accredited laboratory ones. Consequently, both theoretical drop height and peak acceleration appear to be greater than those reported by the accredited laboratory.

For that reason drop height was reduced on test series 3 (*Tab. 5*, *Tab. 7*). Interestingly, Configuration A revealed a higher theoretical drop height in test series 3 compared to accredited laboratory while Configuration B showed the opposite. The velocity ratio r_v of all six Chemnitz testing events remained on a constant level of 0.974±0.006 while the ratio calculated from the accredited laboratory gained results was of 0.813±0.000 for Configuration A respectively 0.906±0.008 for Configuration B.

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Variable	Accredited Lab	Chemnitz Test series 1	Chemnitz Test series 2	Unit
h_m	0.27			m
v_m	1.87±0.00	2.23±0.02	2.25±0.02	m/s
a_m	484.7±4.4	657.8±7.0	669.0±10.9	m/s^2
v_{th}	2.301			m/s
h_{th}	0.178±0.000	0.254±0.004	0.257±0.005	m
r_v	0.813±0.000	0.969±0.008	0.976±0.010	-

Tab. 4: Results for specimen Config. A, h_m=0.27 m (Accr. Lab; Test series 1,2)

Variable	Accredited Lab	Chemnitz Test series 3	Unit
h_m	0.27	0.21	m
v_m	1.87±0.00	1.96±0.02	m/s
a_m	484.7±4.4	454.2±2.25	m/s^2
v_{th}	2.301	2.029	m/s
h_{th}	0.178±0.000	0.196±0.003	m
r_v	0.813±0.000	0.966±0.009	-

Tab. 5: Results for specimen Config. A, h_m=0.27 m (Accr. Lab); h_m=0.21 m (Test series 3)

Variable	Accredited Lab	Chemnitz Test series 1	Chemnitz Test series 2	Unit
h_m	0.50			m
v_m	2.84±0.03	3.05±0.01	3.06±0.01	m/s
a_m	484.4±13.3	940.0±11.9	867.3±24.9	m/s^2
v_{th}	3.132			m/s
h_{th}	0.410±0.007	0.475±0.003	0.478±0.002	m
r_v	0.906±0.008	0.975±0.003	0.978±0.002	-

Tab. 6: Results for specimen Config. B, h_m=0.50 m (Accr. Lab; Test series 1,2)

Variable	Accredited Lab	Chemnitz Test series 3	Unit
h_m	0.50	0.35	m
v_m	2.84±0.03	2.57±0.00	m/s
a_m	484.4±13.3	488.6±3.0	m/s^2
v_{th}	3.132	2.620	m/s
h_{th}	0.410±0.007	0.337±0.000	m
r_v	0.906±0.008	0.981±0.000	-

Tab. 7: Results for specimen Config. B, h_m=0.50 m (Accr. Lab); h_m=0.35 m (Test series 3)

In *Fig. 7: Config. A* and *Fig. 8* mechanical behaviour of the tested materials undergoing consecutive impacts is shown: an increase in peak acceleration a_m during 5 impacts was observed in every Chemnitz laboratory test for both of the materials. The absolute increase appeared to be greater during test series 1 and test series 2 while greater maximum accelerations occurred.

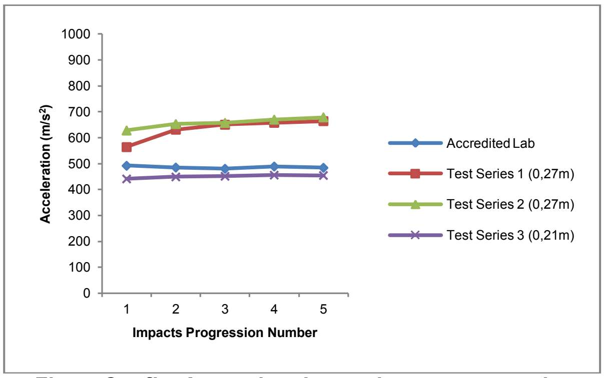

Fig. 7: Config. A, acceleration vs. impact progression number

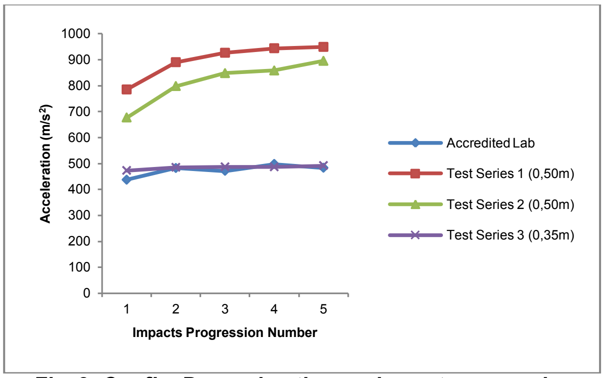

Fig. 8: Config. B, acceleration vs. impact progression number

5 Discussion

Many studies, presented in a review by Mills [16], have proven that foam mechanical properties decrease under multiple impact events. Due to the permanent deformation of the polymer-based foam peak acceleration values increased even with small number of impacts (1 to 15). The same behaviour is displayed in *Fig. 7: Config. A* and *Fig. 8*, giving a sort of validation of the protocol followed to collect the experimental results.

These first results confirm the need to improve the testing procedures to be used on gymnastic equipment by updating the test protocol of EN 913 starting from the experience of the ASTMF1292.

To improve the repeatability properties of the test and the fair comparison of results collected using different testing laboratories, the parameter theoretical drop height h_{th} should be evaluated. Theoretical drop height excludes the influence of friction in the guidance system on the test result and is expected to be lower than the measured (h_m) ones: $h_{th} \leq h_m$. It was calculated by the measured value impact velocity v_m. In EN 913 it is whether not required to install a velocity measurement system nor to obtain impact velocity by any other procedure such as the integration of the acceleration-time trace. So it should be useful to update the standard in this way.

From a safety point of view it is reasonable to declare a material that is characterized by a greater h_{th} as more secure. In this study Configuration B reached the higher value compared to Configuration A when tested both on Test Series 3 and in the accredited lab. In general, it would have been expected that theoretical drop height of either configuration was of the same order for both of the testing institutions.

Furthermore, the introduction of the ratio r_v of measured velocity v_m and theoretical velocity v_{th} enabled to quantify the influence of friction during the fall. In order to ensure comparable testing conditions in all accredited laboratories it is strongly recommended to declare a fixed tolerance.

Finally, due to sources of uncertainty in shock absorption performance evaluation through the most widely used EN 913 protocol, authors are intended to suggest that theoretical drop height, fixed tolerance regarding velocity ratio scores r_v must be taken into account when safety officers, such as managers or technicians as well, are dealt in establishing safety requirements about materials and devices that must be chosen for sport equipment applications.

On the other hand, if theoretical drop height must be not introduced in impact testing protocol, the human head injury risk in case of impact should be underestimated.

6 Conclusion and Outlook

In this work an impact testing apparatus was conceived and built in the laboratories of Chemnitz University of Technology that is able to carry out impact test following both American and European standards protocols. This study has shown the necessity of additional specifications in EN 913 in order to receive valid, reliable and reproducible data. In a pilot investigation of two sample configurations the working principle of the testing device was validated and promising results were gained. Authors are strongly convinced that the laboratory-built apparatus should be useful in further investigations on material prototypes undergoing EN 913 testing. On the other hand it is planned to extend the protocol in order to take head injury risk criterion (ASTM F1292) into account and to correlate test results of the latter with EN 913.

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Paper B

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Improving Passive Safety of Sports Equipment through Experimental Testing of New Protection Devices

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Article Information

Keywords:
Sports Safety
Head Injury Criterion - HIC
Peak acceleration
Drop height
Injury risk index

Abstract

Purpose:
Aim of the paper is to show impact testing experimental results useful to highlight major limitations of passive safety standards for sports equipment and surfaces. These results can be the starting point to define new methods for the assessment and the improvement of passive safety in sports applications, helping technicians in selecting protection devices and in setting functional requirements.

Method:
Experimental tests were carried out through a low-velocity impact testing apparatus, conceived and built in the laboratories of Chemnitz University of Technology. In particular, adopting ASTM F1292 test procedure, the absorption properties of the impact of five polymer-based foams architectures used to cover sports equipment, were tested. These properties are evaluated on the base of impact measures correlated to different level of head injuries. These represent, in fact, the most severe risks to the athlete healthy in case of human body impact.

Result:
The results of the experimental tests showed that, in order to optimize the choice of protection devices on the base of impact absorption properties, it needs to consider together acceleration peak, drop height and Head Injury Criterion (HIC) values.

Discussion&Conclusion:
The joint use of these three parameters is necessary both for producers and technicians in product development process and application, respectively. It was shown that device performances depend on drop height magnitude: for each sport discipline, it is important to define the critical fall height of use or the maximum impact energy amount which could be experienced by athletes during sport practice. Finally, a new injury risk index, functionally related to previous performance parameters and a simple eco-sustainable approach in selecting the optimal device were proposed.

1 Introduction

Sport is one of the most widespread leisure activities of European citizens, a common cultural element of modern societies and an important social and economic phenomenon.

The European Parliament estimated that sport counts for estimated 3.6% of the Community Gross National Product (GNP) in EU countries [1].

On the other hand, sport accounts for a considerable number of injuries: in [2] it was estimated that 14% of all medically treated injuries are related to sport and in [3], based on European hospital Injury Database (IDB) is estimated that annually almost 6 million persons need treatment in a hospital due to an accident related to sportive activity, of whom 10% require hospitalization for one day or more. Such data lead to the calculation, for the direct medical costs in the European Community, of at least 2.4 billion Euro.

Although the burden of sport injury is economically relevant, from a public health point of view, it is necessary to analyse the problem for adopting all the prevention possible actions. In fact, based on the Eurostat and World Health Organization (WHO) mortality databases, the number of fatal sport injuries is very high and can be estimated at 7.000 fatalities per year.

Education and information, the so called “active strategies” of prevention, play an important role in injury prevention, but in general, there are other, and in most cases even more effective prevention strategies available like e.g. the use of protective device in sports area, the so called “passive safety strategies”.

Generally, the situation in sport is the same of other sectors like road transport, where accidents and injuries occur as unwanted side effects.

In sport, falling and stumbling played an important role in the total amount of accident mechanism (more than 30%) while significant share of head injuries were observed in basketball, soccer, ice hockey, cycling and many others [3].

According both sport safety international standards [4, 5] and biomechanical studies [6], head injuries represented the most severe risks to the athlete healthy in case of human body impact on sport surfaces.

To this end, head injury risks evaluation indexes were well studied in Biomechanics efforts through an acceleration-time trace during head impact monitoring. Therefore, standardized methods to perform impact tests were introduced by American and European Organizations in order to characterize impact attenuation properties of protective device used in Sports field.

In the paper five polymer-based foams architectures, generally used to cover sports equipment, were tested through a low-velocity impact testing apparatus, following standardized procedure requirements.

Aim of the paper is to use these experimental results as starting point to define new methods for the objective assessment of the passive safety in sports area, which allow, taking into account several parameters, protection materials comparison and choice.

2 Head Injury Models

In the design processes of the head protective devices (e.g. helmets), tolerable head impact limits, that could be related to serious injuries or death, are required. The head acceleration, as function of time, following an impact event, is considered as reference parameter for measuring the severity of head injury, well-known in the literature as Head Injury Model (HIM) [7].

2.1 Acceleration Peak

This simple method, based on the maximum acceleration recorded during an impact event, utilizes only a single point on the acceleration-time waveform called peak (g). The duration of the impact pulse is not considered while, in Physics, this last one contributes to characterize impact attenuation properties of protective surfaces. In Fig. 1, two different acceleration graphs (each related to different materials density) are shown for a given impact energy value.

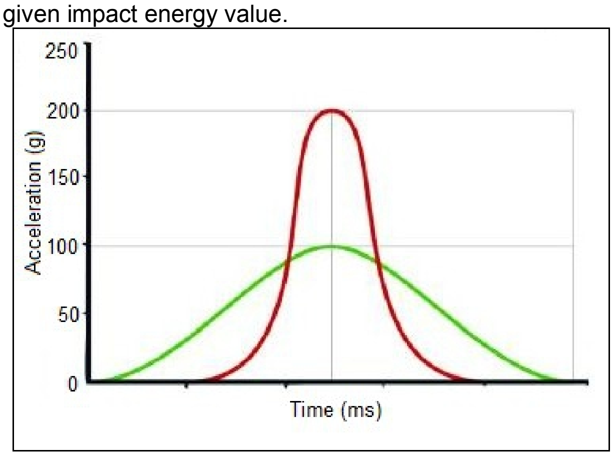


Fig. 1 Acceleration-Time trace for two different materials densities: soft surface (green line); hard surface (red line)

A relatively high acceleration peak indicates low absorption properties of the protective surface and the impact event lasts for a short period of time (red line on the graph). High absorption performances appear to be reached in correspondence to relatively lower acceleration peaks and longer impact time period (green line on the graph).

Lisner et al. [8] have experimental demonstrated that the severity of head injury is dependent both on the magnitude and the duration of impact. To this end, in Fig. 2 the Wayne State Tolerance Curve is shown. Points above the curve are considered danger to life, instead of those below that are tolerable. Many literature references agree on a maximum acceptable acceleration value of 50 g before injury threshold while an acceleration peak value of 200 g represents a limit before fatal injuries.

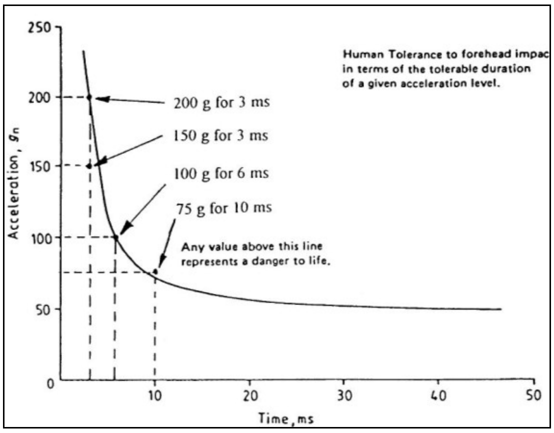


Fig. 2 Human tolerance to for head impact in terms of the tolerable duration of a given acceleration level [7]

2.2 Head Injury Criterion

The Head Injury Criterion (HIC) is used to evaluate the injury level of the pedestrian head when it is calculated as the linear acceleration observed at the center of mass of the head of an anthropomorphic test device seated in a vehicle that collides with a fixed rigid barrier. The HIC considers the more injurious portion of the impact waveform, the peak and close to peak section and it has been introduced in 1971 [9].

It is defined as:

$$\mathrm{HIC} = \max \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} (t_2 - t_1) \qquad (1)$$

Where (t_2-t_1) is the portion of waveform to be measured during which HIC attains maximum value; a(t) is the acceleration on impact (in units of gravity g); dt is the duration of acceleration on impacts (ms).

An experimental program conducted by Prasad and Mertz [10] has shown correlation between HIC scores and different head trauma levels through an index called Abbreviated Injury Score (AIS). In Fig. 3 six different risk of life threatening brain injury curves (and related HIC values) are shown.

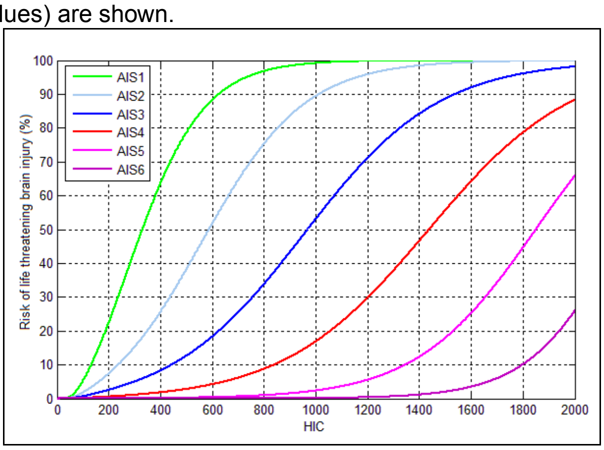


Fig. 3 Probability of Brain Injury vs HIC scores for AIS=1 to AIS=6 (minor injury to fatal injury)

The HIC score of 1000 is defined as that value corresponding with a probability of 16% of life threatening brain injury (AIS=4).

HIC scores are also used as measured parameters in EuroNCAP testing procedures of pedestrians frontal impact assessment [11]. Following “Frontal and Side Impact” assessment procedure (head and neck section), is possible to build an overall star rating that evaluates cars impact performance when a fiftieth percentile male dummy is used and HIC scores are calculated.

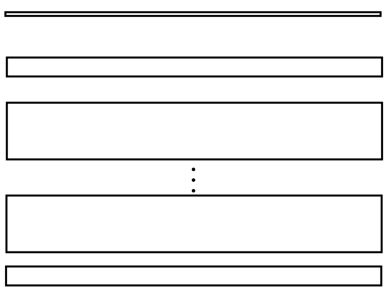
3 Materials and methods

Using a low-velocity impact testing apparatus, conceived and built in Sports Equipment and Technology Department of Chemnitz University of Technology and adopting ASTM F1292 test procedure [12], experimental impact tests on five different sandwich configuration of polymer-based foam sport protective devices were carried out.

3.1 Specimens

Specimens under test were available in a sandwich configuration with overlapped layers (hot melted) made of fully cross-linked polyethylene closed cell foam (PE), dimension 50 cm x 50 cm and variable thickness.

In Tab.1 a building scheme is shown with materials specifications.

Layer Name	Sandwich				Presence
Cover Top Core Down					Yes or Not Yes or Not Regular or Irregular Yes or Not
Layer Name	**Layer Quantity**	**Layer Type**	**Layer Material**	**Layer Density**	**Layer Thick.**
Cover	1	Full	PVC		thin
Top	1	Full	PE	low high	medium
Core	1-4	Full	PE	low high	thick
	1-4	Cut	PE	low	thick
Down	1	Full	PE	low high	medium

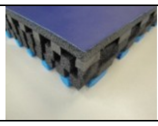
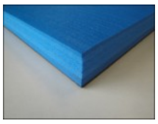
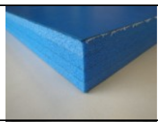
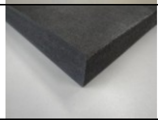
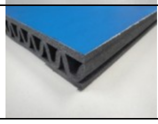
Tab. 1 Sandwich building scheme and material properties

Depending on cover, top and down layer presence, core layer type (full, cut or wave) and layer densities choices, it has been possible to identify several sandwiches units (architectures).

In Tab. 2 are shown architectures under test: layers number, densities, weight and covering specifications.

3.2 Impact Testing Protocol

Impact tests under a velocity range from 1 to 10 m/s [13] were carried out using the low velocity impact testing apparatus.

Arch. Name	Photo	Layers Number	Layers Density	Arch. Weight (kg)	Cover
A		5	1°-low Reg. 2°-low Irreg. 3°-low Irreg. 4°-low Irreg. 5°-low Irreg.	0.559	PVC
B		6	1°-high Reg 2°-low Reg. 3°-low Reg. 4°-low Reg. 5°-high Reg. 6°-low Reg.	0.655	NO
C		4	1°-low Reg. 2°-low Reg. 3°-low Reg. 4°-low Reg.	0.404	PVC
D		5	1°-high Reg. 2°- highReg. 3°- highReg. 4°- highReg. 5°- highReg.	1.115	NO
E		3	1°-low Reg. 2°-low Irreg. 3°-low Reg.	0.389	PVC

Tab. 2 Architectures Specifications

Several impact test series (3 sequential impacts each) were performed from different drop height in order to meet, finally, both the acceleration and the HIC performance criterion specified in ASTM F1292 Standard.

To this end, an hemispherical missile was designed, manufactured and used (Fig.4).

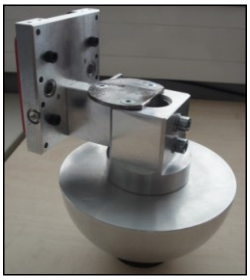


Fig. 4 Impact testing support assembly

The head of the striker was attached to a support assembly, both connected to a lifting carriage (guidance system) which raised the drop assembly to a first trial measured height ($\boldsymbol{h_m}$). At this height, the whole drop assembly was uncoupled (through an electro-magnetic releasing device installed in the test rig) and fell under gravity by a vertical guidance system on the center of a sample that was fixed by double-sided adhesive on a steel plate (anvil) in order to limit the overall bending of the specimen. All test pieces were conditioned for a minimum of 3 h at the test temperature of 23±2 °C. The impact velocity ($\boldsymbol{v_m}$) was measured by a laser displacement sensors sited along the path of the striker, just above the specimen. Sequential interruption of the laser beam by a plate attached to the falling striker triggered the starting and stopping of a counter-timer. The impact velocity was determined from the elapsed time and the plate height. In order to measure drop assembly deceleration ($\boldsymbol{a_m}$), the testing rig was equipped with a piezoelectric accelerometer (rigidly mounted into the missile through a PE high density threaded shaft) connected to a data acquisition PC computer for post-processing acceleration as a function of time. ***HIC*** value was also calculated through formula (1). The specimen under examination was subjected to three consecutive low velocity impacts, with an interval of 1.5 min. All acceleration-time traces were examined to ensure that it contained no spurious peaks. Furthermore, prior to the onset of impact, it was verified that the recorded acceleration value was 0±20 m/s^2 and the acceleration waveform descended from its maximum value to a stable value of 0±20 m/s^2 without overshooting the zero baseline by more than 20 m/s^2. In order to take into account friction influences in the guidance system, also theoretical velocity and drop height values, velocity ratio values ($\boldsymbol{v_{th}}$, $\boldsymbol{h_{th}}$, $\boldsymbol{r_v}$) were calculated in a post-process phase.

Afterwards, several impact test series trials were carried out by increasing measures drop height values. The whole impact testing procedure ended when the critical fall height $\boldsymbol{h_{cr}}$ (maximum of $\boldsymbol{h_m}$) was reached and the acceleration performance criterion of 200g and HIC performance criterion of 1000 were met. All adopted symbols and impact testing units are shown in Fig. 5 and Tab. 3.

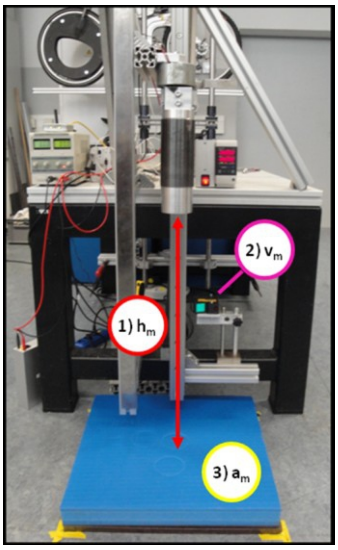


Fig. 5 Impact testing apparatus units

Trials Parameter	Description	Formula
h_m	Drop height fixed before the starting impact testing series	no formula (measured)
v_m	Missile velocity before the contact with the specimen	no formula (measured)
a_m	Peak acceleration during the impact event	no formula (measured)
h_{th}	Drop height that produces a velocity of v_m (free-fall)	$h_{th} = \frac{v_m^2}{2g}$
v_{th}	Missile velocity in a free-fall from an height of h_m	$v_{th} = \sqrt{2gh_m}$
r_v	Measured and theoretical velocity ratio	$r_v = \frac{v_m}{v_{th}} < 1$
HIC	Head Injury Cryterion Score	(1)

Tab. 3 Adopted symbols

4 Results

Impact tests were performed on five different layer configurations, named Architecture A,B,C,D,E (shown in Tab. 2), during several trial series of drops (each trial series counted three consecutive drops from the same drop height with an interval time of 1.5 min). Values of the last 2 on a series of 3 impacts were collected (in terms of variables shown in Tab.3) to calculate arithmetic mean for each architecture.

In order to meet acceleration performance criterion of 200g and HIC performance criterion of 1000, first trial series drop heights were increased till the critical one was reached.

In Tab.4, all critical collected data (mean values) for all the tested architectures are shown.

Variable	Arch.A	Arch.B	Arch.C	Arch.D	Arch.E
h_m (m)	2.000	2.400	1.750	2.200	0.900
v_m (m/s)	5.43	5.95	5.10	5.72	3.63
a_m (g)	189.19	192.3	201.4	180.2	185.5
HIC	666.5	1096.5	826.5	1029	382
h_{th} (m) = h_{cr}	1.503	1.805	1.329	1.662	0.674
v_{th} (m/s)	6.26	6.86	5.86	6.57	4.20
r_v	0.867	0.867	0.870	0.871	0.864

Tab. 4 Critical data sheet for Architecture A,B,C,D,E

Measured drop heights (h_m) appeared to be different from the theoretical ones (h_{th}) as expected: due to guidance system friction influences, measured impact velocities (v_m) were lesser that theoretical ones (v_{th}) and velocity ratio (r_v) remained on a constant value of 0,868±0.003 (m/s) that ensured comparable tests boundary conditions (in terms of friction influence) during the whole experimental session.

Interestingly, Architectures A,C,E were characterized by acceleration peak values close to the requested performance criterion of 200g while the HIC values were far from the requested performance criterion of 1000.

In Figg. 6 and 7, critical fall height and HIC performances of all the five architectures are shown.

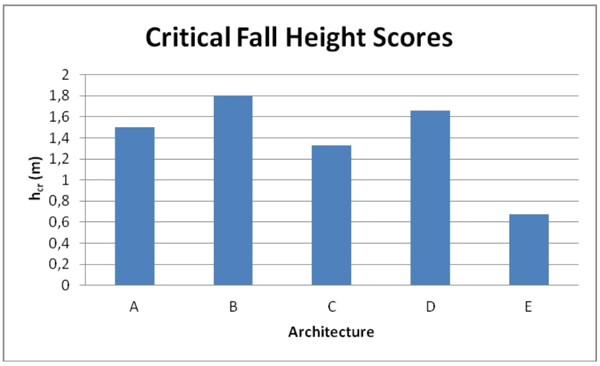


Fig. 6 Critical fall height Architecture performances

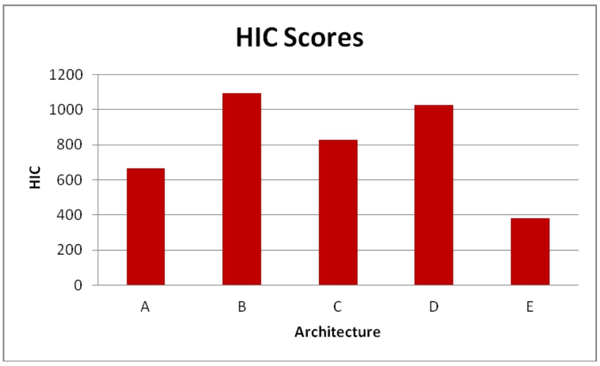


Fig. 7 HIC Architecture performances

Due to a low number of specimens, it has not been possible to achieve HIC scores close to the performance criterion of 1000 for architectures A,C,E.

In Figg. 8 and 9, referring to architecture A, an acceleration peaks vs drop height values plot and an HIC vs drop height values plot have been obtained through an exponential curve fitting process: as expected, acceleration peaks and HIC plots have shown an increasing trend. These last performances trends were confirmed also for the architectures C,E. So by increasing of drop heights in order to obtain greater scores of HIC, acceleration peaks should be greater than the previous value of 200g and both performance criterions should not have centered simultaneously.

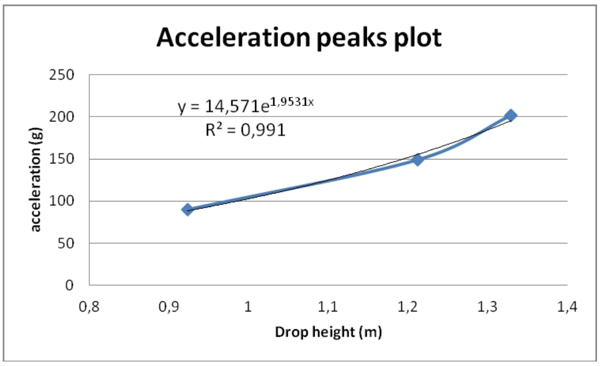


Fig. 8 Acceleration peaks vs drop height values plot

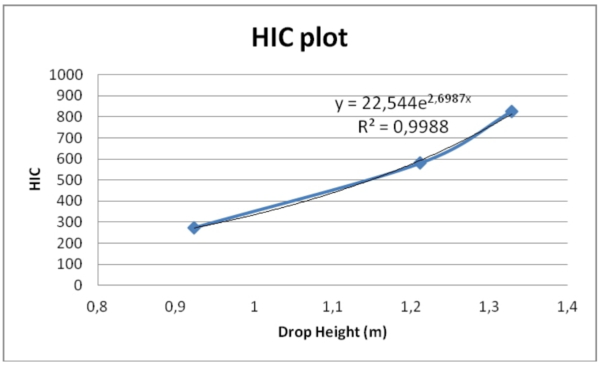


Fig. 9 HIC vs drop height values plot

In Figg. 10 and 11, referring to architectures B and D, that have shown best performances than the others, as highlighted in Fig.6, it has been done a comparison between HIC and acceleration peak performances evaluated for two different drop heights (both lesser than architectures B and D critical ones).

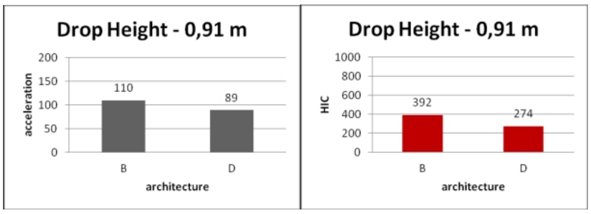


Fig. 10 Architecture B and D comparison in term of HIC and acceleration peaks performances from the same drop height 0.91 m

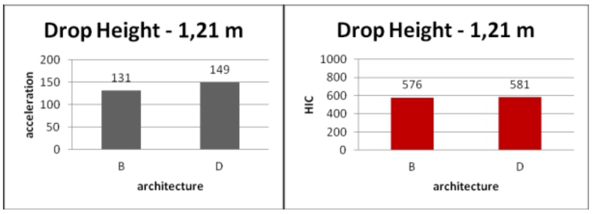


Fig. 11 Architecture B and D comparison in term of HIC and acceleration peaks performances from the same drop height 1.21 m

Architecture B is characterized by greater values of acceleration peak and HIC than Architecture D from a drop height of 0.91 m.

On the other hand, Architecture D has shown greater performances at drop height of 1.21 m.

Finally, in Fig. 12, the ratio between critical fall height (Cfh) and weight, for all of the tested architectures has been considered [17, 18].

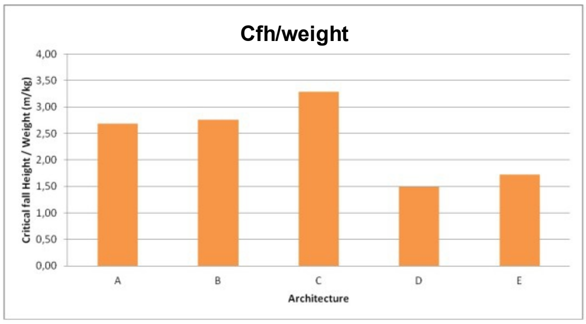


Fig. 12 Architecture performances in term of efficiency of use of the material

5 Discussion

Many Sports Safety standards, i.e. for gymnastic equipment [5], for playground surfaces [14], for football helmets [15], faced on impact attenuation properties evaluation of protective devices, define drop height as the vertical distance between the lowest point of the impactor and the apex of the impact surface. According this definition, certified critical fall heights overestimate theoretical ones, that take into account guidance system friction influences (Tab. 4).

Impact test results for architectures analyzed in this study have shown that both acceleration performance criterion and HIC performance criterion were not reached simultaneously: specimens A,C,E acceleration peak values, in fact, were approximately 200g while related HIC values were markedly lesser than 1000. A similar study [16] on polymer based-foam mats has confirmed these performances behaviour.

In order to take exhaustively into account head impact injury risks, an HIC values and acceleration peaks joint monitoring is requested: it could happen, in fact, that HIC values are lesser than 1000 while acceleration tolerable peaks are exceeded.

A particular comparison between architecture B and D scores has shown that the best performances of architecture B in correspondence of a critical fall height are not confirmed at different drop height. From safety assessment point of view, it is recommended to evaluate protective devices performance parameters by introducing a reference drop height that agrees with protective device use [15].

From the efficiency of material use point of view it is possible to observe that Fig. 12 shows a new ranking among the five architectures compared to that one shown in Fig. 6 in terms of critical fall height.

In particular architecture C becomes more efficient from the material use point of view and architecture D, second in terms of critical fall height, becomes the last in term of efficiency of use.

From the analysis of the results, it is possible to define a new injury risk index, whose formulation it should depend on Head Injury Criterion values (HIC), acceleration peaks (a_m) and critical drop height of use (h_u).

6 Conclusion

At present the safety of protection devices in sports area is assessed according to sport safety standards associated with their specific use. However, the different sport safety standards do not propose a method for assessing the safety which allows to define the degree of safety achieved but they just specify a criterion of conformity of use.

With reference to the Head Injury Models, in the paper, thought experimental impact tests, it was demonstrated that, in order to quantify the injury risk for a protection device, it is not possible to consider separately the peak acceleration, the drop height and the HIC.

This new approach, applicable to different sports disciplines, will allow to define appropriate injury risk indexes, as a function of peak acceleration, drop height and HIC.

Finally, further works will be addressed to take into account also the eco-sustainability of the product, as an important parameter in selecting the optimal device.

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Paper C

G. Costabile, G. Amodeo, M. Martorelli, A. Lanzotti, S. Odenwald, S. Schwanitz, *"Toward a new Approach for Passive Safety Assessment of Gymnastic Equipment."*, AMME International Scientific Conference on Achievements in Mechanical and Materials Engineering, Gliwiche-Krakow, Poland, June 23th – 26th, 2013, 8 pp., invited paper, 2013.

Toward a New Approach for Passive Safety Assessment of Gymnastic Equipment

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Abstract

Purpose
Aim of the paper is to propose a new approach for the assessment of passive safety of gymnastic equipment that allows technicians to optimize the choice of protection devices. On the base of a new procedure, defined to evaluate the impact absorption properties of materials and architectures of protection devices, it has been possible to highlight the limitations of current safety international standards.
Design/methodology/approach
According to different standard procedures, EN 913 and EN 1177 with an additional control on the acceleration parameter, experimental tests on polymer foam materials were performed using cylindrical and hemispherical missiles connected to a flexible impact testing apparatus realized at Chemnitz University of Technology.
In particular, considering EN913 test procedure, trial impact testing consecutive series were carried out in order to find the critical fall height that complied the performance criterion of an acceleration peak value lesser than 50 g. On the other hand, considering EN 1177 test procedure, trial impact testing consecutive series were performed in order to establish the maximum value of drop height (critical drop height) that finally caused Head Injury Criterion (HIC) scores lesser than 1000: in this case an additional monitoring was paid on each impact series acceleration-time traces and the performance criterion of 200 g was registered.
Findings
Impact tests carried out using cylindrical and hemispherical missiles have shown, for the same impact energy, different acceleration peak values, always greater for hemispherical missile than cylindrical one. So considering EN 913 procedure, the severity of head impacts, in term of acceleration peak can be underestimated when a cylindrical missile is used. For this reason to correctly assess the head injuries is necessary to take into account in addition to the acceleration peak value, also HIC parameter. Furthermore it has to consider also the effect of the friction of the guidance system measured because it does to overestimate the impact energy and so to underestimate the damage.
Research limitations/implications
The research described in the paper was carried out taking into account only the human head impacts (the most severe injuries) and not other parts of the human body. Furthermore at present the assessment of the brain injury risks in Sport area is performed through HIC scores taking into account the automotive knowledge obtained, in the last decades, simulating human head impacts by using 50^{th} percentile male dummies.
Practical implications
The new approach proposed in the paper can be useful for the choice of the protective devices to improve the passive safety of gymnastic equipment. It represents a starting point to define new standards.
Originality/value
On the base of experimental tests, the authors show that the safety threshold of peak acceleration defined in the EN913 standard is poor. For this reason it is necessary to modify the current standards, in order to guarantee an adequate passive safety and to allow the technicians to optimize the choice of protection devices on the base of impact absorption properties, that are evaluated using all together the parameters: acceleration peak, drop height and Head Injury Criterion (HIC).
Keywords:
Design Methods, Sport Safety, Polymer Foam, Impact Test, Head Injury Criterion.

1. Introduction

At present the safety of protection devices in sports area is assessed according to sport safety standards associated with their specific use. In Tab. 1 a comparison among several international standards [1-6], characterized by different application fields (from playground surfacing systems to general playing systems) but by the same dynamic impact testing apparatus join them, is shown.

Today these standards represent the only reference that a technician can use in selecting of the protection devices materials and architectures.

Moreover recent studies highlighted some limitations of current passive safety standards for sports equipment and surfaces.

In [7] it was investigated if the testing procedure given by European standard EN 913 [6] was sufficient to lead to comparable results, in case of materials being tested by different laboratories and the results showed clearly the necessity of additional specifications in order to receive valid, reliable and reproducible data.

It was recommended to extend the protocol in order to take head injury risk criterion into account (as in ASTM F1292 [1]) and to correlate test results of the latter with EN 913.

In [8] the results of the experimental tests showed that the technician, in order to optimize the choice of protection devices on the base of impact absorption properties, has to consider the joint use of three parameters: acceleration peak, drop height and Head Injury Criterion (HIC).

These limitations in standards, combined with the few papers in literature and with the lack of a method for assessing the safety which allows to define the degree of safety achieved, have stimulated the authors to develop a new approach for the materials and architectures choice, in particular to guarantee the safety of gymnastic equipment.

2. Background

A recent study [9] on sport injuries in the European Union showed that annually, almost 6 million persons needed hospital treatment due to accidents related to Sports activities. Based on the Eurostat and WHO mortality databases, in fact, the number of sports fatalities can be estimated at 7000 per year and Team ball sport account for about 40% of all hospitalizations. The most severe injuries are related to the head and arise mainly (30%) due to impacts (falling, stumbling) with the ground/surface, equipments or opposite players.

While severe head injuries are relatively rare, they have the potential to change lives in a dramatically way. For this reason the sports community had to pay attention to risks assessment and provide prevention requirements to improve passive safety of sport equipment. To this end protection devices, mainly produced in polymer foam, are required to guarantee passive safety.

From a biomechanical standpoint, many authors [10-12] have analysed and provided brain injury risks indexes trough mathematical models, Head Injury Models (HIM), based on the observed responses of cadavers, animals or accident victims during head impact experiments or simulations.

Lisner et al. [13] have experimental demonstrated that the severity of head injury is dependent both on the magnitude and the duration of impact. The relationship between the acceleration level and time duration with respect to head injury is known as Wayne State Tolerance Curve (WSTC).

The region above the curve is considered danger to life because belong to it critical conditions for both magnitude and duration. The region below the curve is considered tolerable. Many literature references agree on a maximum acceptable acceleration value of 50 g before injury threshold while an acceleration peak value of 200 g represents a limit before fatal injuries.

These data were used by Gadd in 1961 [14] and an approx. straight line function was developed for the weighted impulse criterion that became known as the Gadd Severity Index (GSI). Afterwards, Versace in 1971, defined a new parameter, the Head Injury Criterion (HIC) that is currently used to assess head injury risk in automotive crash test, as following:

$$\mathrm{HIC} = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}(t_2 - t_1) \qquad (1)$$

where (t_2-t_1) is the time interval in which the acceleration time curve (Fig.1) numerically calculated, attains the maximum value of the integral; a(t) is the acceleration on impact (in units of gravity g).

Table 1.
Sport Safety International Standards Comparison

Standards	ASTM F1292	ASTM F355	ASTM F2440	ASTM F1936	EN 1177	EN 913
Application Field	Playground Surfacing	Playing Surface Systems	Wall/Feature Padding	Football Field Playing Systems	Playground Surfacing	Gymnastic Equipment
Impact Testing Apparatus.	Dynamic Drop Tester Device					
Missile	Hemispherical Radius=160mm Mass=4.6kg	Cylindrical Radius=64mm Mass=9.1kg	Hemispherical Radius=160mm Mass=4.6kg	Cylindrical Radius=64mm Mass=9.1 kg	Hemispherical Radius=160mm Mass=4.6kg	Cylindrical Radius=75mm Mass=8 kg
Performance Parameter.	HIC, G_{max}	HIC, G_{max}	HIC, G_{max}	G_{max}	HIC	G_{max}
Performance Criterion	HIC<1000 G_{max}<200g	HIC<1000 G_{max}<200g	HIC<1000 G_{max}<200g	G_{max}<200g	HIC<1000	G_{max}<50g

Empirically determined relationships between HIC scores and the probability of head injury were observed and analysed by Prasad and Mertz [15] during an experimental program where different probability of head injury curves related to different head trauma levels are shown.

The HIC score of 1000 is defined as that value corresponding with a probability of 16% of life threatening brain injury (AIS=4) and is fixed as a reference value for life threatening head injury threshold.

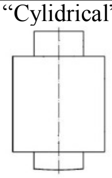
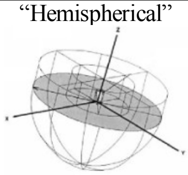
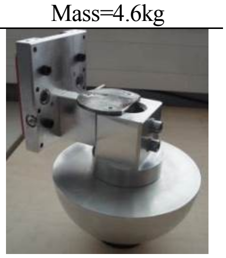
The potential for head injury had an influence on the development of sports protective devices and a shock attenuating surfaces evaluation began in 1975 when the US Consumer Product Safety Commission (CPSC) published its first hazard analysis and safety guidelines for playgrounds. In several cases, International organizations for standardization (i.e., International Organization for Standardization, ISO, American Society for Testing material, ASTM and European Commitee for standardization, CEN) provide standard test methods used to evaluate shock attenuation properties of sports protective materials and to minimize head injury risks through an appropriately cushioned surface installation.

3. Materials and methods

An impact testing experimental program on polymer foam materials was followed at Sports Equipment and Technology department, SGT of the Chemnitz University of Technology laboratory () where an apparatus [7] was designed and built.

In order to carry out experiments during two different impact testing phases, the procedures that have been adopted referred to the EN 913 [6] and the EN 1177 [5] with an additional control on the acceleration parameter. A brief focus on both standards apparatus units, procedure requirements and adopted apparatus units, is shown in Tab. 2.

Table 2.
EN 913 and EN 1177 procedures requirements

Standard	EN 913	EN1177
Performance Parameter	Acceleration G_{max}	HIC
Performance Criterion	$G_{max} < 50$ g	HIC< 1000
Standard Missile	"Cylidrical"  Diam.=75mm Mass=8kg	"Hemispherical"  Diam.=160mm Mass=4.6kg
Adopted Missile	 Mass=7991g	 Mass=4623g

According to single units apparatus descriptions [7] is useful to underline that the main functional requirements adopted during the design phase was the impact testing devices parts interchangeability: the so built apparatus, in fact, was capable to comply the two previous standards procedures by changing the missile (cylindrical and hemispherical). Performance parameters were controlled and analysed through a piezoelectric transducer (accelerometer) fixed inside the missiles and a record system that allowed to show an acceleration-time trace signal.

An example of acceleration graph is shown in Fig.1.

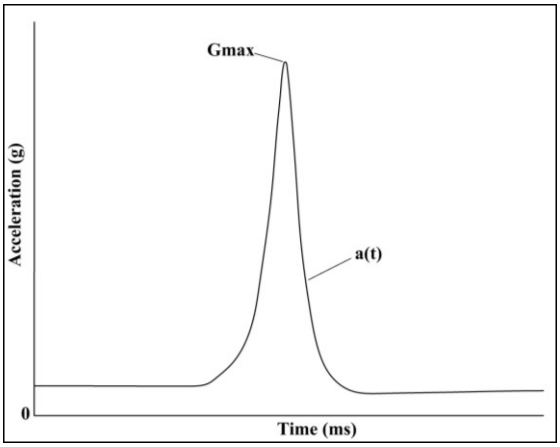


Fig. 1 Acceleration-Time curve

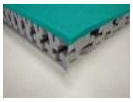
3.1. Materials

Specimens under test (50x50cm) were structured in a sandwich mode through hot-melted layers overlapping. Each layer was made of a polymer-based foam named "fully cross-linked Polyethylene closed cells" (PE). A typical sandwich structure was composed by a special varnish as covering, a top and bottom full layer that sustained a core cut layer section: depending on varnish application (yes/no), top layer density (low. medium, high), core layer number and bottom layer presence (yes/no), several material architectures were available to test (A,B,C,D,E,F,G,H in Tab.3) in four thickness categories (thin, intermediate, normal and thick).

3.2. Impact Testing Procedures

Impact tests were performed through a flexible low-velocity impact testing apparatus [16] according two different standard procedures, EN 913 and EN 1177 with an additional control on the acceleration parameter. From EN 913 point of view, trial impact testing series [7], each composed by five consecutively impacts with a time interval of 1.5 min, were carried out in order to find a drop height (named critical drop height) that finally complied the performance criterion of an acceleration peak value lesser than 50 g. On the other hand, from EN 1177 point of view, a similar to the previous procedure was adopted [8] through trial series of three consecutive impacts each, in order to establish which drop height (critical drop height) finally caused HIC scores lesser than the performance criterion of 1000: in this case, additional attention was paid on each impact series acceleration-time trace monitoring, related peak values registering and, finally, the performance criterion of 200 g was implemented. All of the controlled (measured) and post-processed parameters are shown in Tab.4.

Table 3.
Specimen Architectures

Name	Photo	Layer Number-Density- Type	Thickness	Cover
A		1 - low - full. 2 - low - cut. 3 - low - cut.	thin	no
B		1 - low - full. 2 - low - cut. 3 - low - cut.	thin	yes
C		1 - high - full. 2 - low - cut. 3 - low - cut. 4 - high - full.	intermed.	no
D		1 - high - full. 2 - low - cut. 3 - low - cut. 4 - high - full.	intermed.	yes
E		1 - med. - full. 2 - low - cut. 3 - low - cut. 4 - low - cut. 5 - low - cut.	normal	no
F		1 - med. - full. 2 - low - cut. 3 - low - cut. 4 - low - cut. 5 - low - cut.	normal	yes
G		1 - high - full. 2 - low - cut. 3 - low - cut. 4 - low - cut. 5 - low - cut. 6 - high - full.	thick	no
H		1 - high - full. 2 - low - cut. 3 - low - cut. 4 - low - cut. 5 - low - cut. 6 - high - full.	thick	yes

Afterward, in order to compare both of previous procedures parameters values, drop heights (h_{eq}) equivalent to EN 913 critical fall heights were calculated for EN 1177 procedure by equating impact energies [17] (fuctionally related to each missile masses) as following:

$$h_{eq} = \frac{m_{cylind.}}{m_{hemisp.}} * h_{cr} \qquad (2)$$

Table 4.
Trials Parameter

Symbols	Description	Measured/Calculated
h_m	Drop height fixed before starting impact testing trial series	measured
v_m	Missile velocity before the contact with the specimen	measured
a_m	Peak acceleration during the impact event	measured
h_{th}	Drop height that causes a velocity of v_m (free-fall)	$h_{th} = \frac{v^2_m}{2g}$
v_{th}	Missile velocity in a free-fall from an height of h_m	$v_{th} = \sqrt{2gh_m}$
r_v	Measured and theoretical velocity ratio	$r_v = \frac{v_m}{v_{th}} < 1$
HIC	Head injury criterion score	(1)

Finally, empirically equations [18] for the evaluation of head injury trauma levels (AIS values) were implemented in MATLAB software starting from input HIC scores.

$$\begin{aligned} AIS1 &= [1 + \exp((1.54 + 200 / HIC) - 0.0065 * HIC)]^{-1} \\ AIS2 &= [1 + \exp((2.49 + 200 / HIC) - 0.00483 * HIC)]^{-1} \\ AIS3 &= [1 + \exp((3.39 + 200 / HIC) - 0.00372 * HIC)]^{-1} \\ AIS4 &= [1 + \exp((4.9 + 200 / HIC) - 0.00351 * HIC)]^{-1} \\ AIS5 &= [1 + \exp((7.82 + 200 / HIC) - 0.00429 * HIC)]^{-1} \\ AIS6 &= [1 + \exp((12.24 + 200 / HIC) - 0.00565 * HIC)]^{-1} \end{aligned} \qquad (3)$$

4. Results

Impact tests were performed on 8 architectures shown in Tab.3, according to both procedures EN 913 and EN 1177 by using cylindrical and hemispherical missiles, respectively.

Following EN 913 protocol several trials series of drops were carried out from increased drop heights (for each specimen) in order to achieve the critical one that produced an acceleration peak of 50g.

According to formula (2), equivalent drop heights were calculated to perform, through the hemispherical missile, following EN 1177 protocol, the second trials series,.

Fig. 3 shows the critical drop height experimentally obtained and the height obtained by the equation (2).

Fig. 4 shows the equivalent acceleration peaks that were greater than performance criterion of 50 g for all of specimens under study. For this reason it is necessary to evaluate HIC values and head injury trauma levels according to the equations (1) and (3) respectively, following EN 1177 procedure (see Tab. 5).

Equivalent heights appeared to be greater than Critical ones due to minor mass of the hemispherical missile compared with cylindrical one.

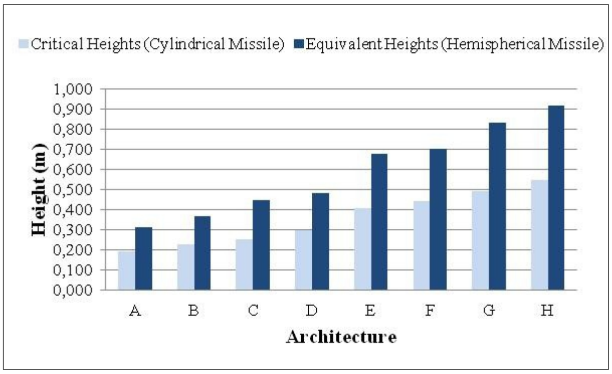


Fig. 3 Critical Heights (EN 913) compared to Equivalent Heights (EN 1177)

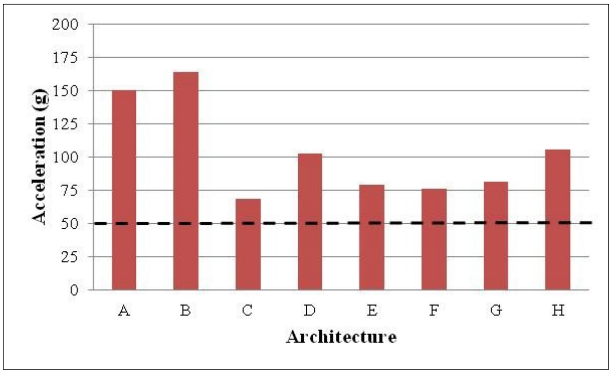


Fig. 4 Hemispherical Missile Accelerations measured from Equivalent Heights

Table 5.
HIC and AIS scores evaluated from equivalent heights (h_{eq}) by using Hemispherical Missile procedure, for each layer architecture.

	A	B	C	D	E	F	G	H
h_{eq} (m)	0.311	0.366	0.444	0.479	0.676	0.700	0.832	0.917
HIC	165	236	113	195	158	164	203	291
AIS1 (%)	15.53	29.45	6.78	21.25	14.27	15.35	22.84	41.25
AIS2 (%)	5.13	9.85	2.29	7.02	4.72	5.07	7.55	14.35
AIS3 (%)	1.80	3.31	0.83	2.41	1.66	1.78	2.59	4.71
AIS4 (%)	0.39	0.72	0.18	0.52	0.36	0.39	0.56	1.02
AIS5 (%)	0.02	0.05	0.01	0.03	0.02	0.02	0.04	0.07
AIS6 (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

According to Abbreviated Injury Scale (AIS) definitions, each layer architecture has shown a probability not equal to zero percentage that minor brain injuries occurred (AIS1 values in Tab.5). More severe injuries (from moderate to critical) appeared to be characterized by considerable probability from major drop heights (AIS2,3,4,5 scores in Tab.5). Not significant probability that a fatal injury occurred was achieved for all of the architecture under test.

During a second experimental program phase, drop heights were arranged (by increasing) in order to comply the performance criterion of EN 1177 procedure by using the hemispherical missile and registering HIC and also related acceleration peaks values. In Fig. 5 HIC scores registered from drop heights that produced acceleration peaks of 200 g are shown.

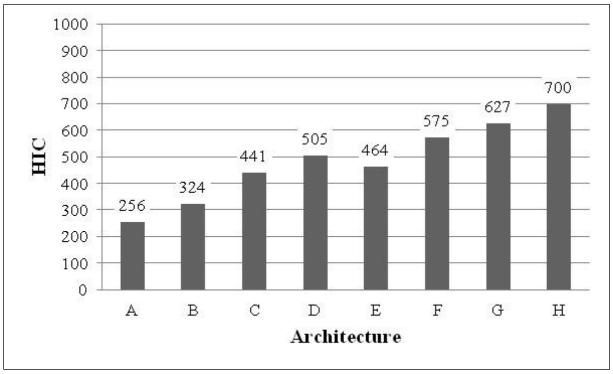


Fig. 5 HIC scores related to acceleration peaks ≈ 200g

No layer architecture met the performance criterion of HIC=1000 (showing considerable difference between evaluated HIC scores and the criterion of 1000 in Fig. 5) when the acceleration peaks achieved a maximum value of 200g.

Furthermore, measured velocity values before impacts were always lesser than the theoretical ones (the latter defined in Tab.4) and, due to friction influence in the guidance system, theoretical drop heights were calculated and compared to measured ones, as in Fig. 6.

Finally, a numerical procedure was implemented in order to estimate impact testing outcomes through a simple exponential model that fits real experimental data. In Fig. 7, starting from three collected (real) impact testing data series in term of acceleration peak, a fourth data series was simulated by fitting real measures with exponential function and by using exponential formula in order to find the correspondent drop height to the acceleration performance criterion of 200g (h=1.510 m in Fig.7) and the correspondent HIC value to this evaluated drop height (HIC = 627.5 in Fig.8). By using these last outcomes, a further impact testing series was carried out in order to compare simulated and real data in terms of percentage variation.

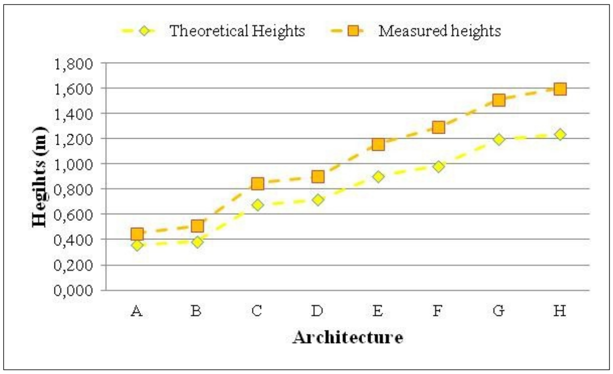


Fig. 6 Measured and Theretical Drop Heights Comparison

In Tab. 6 an example of the evaluated outcomes through the numerical and the real impact testing procedure is shown for the architecture G.

Table 6.
Comparison between numerical and real impact testing procedure outcomes for architecture G and referring to a measured drop height of 1.510 m

Parameter	Numerical Procedure	Real Impact Testing Procedure	Percentage Variation (%)
Theoretical Drop Height h_{th} (m)	1.191	1.194	-0.26
Measured Velocity v_m (m/s)	4.82	4.84	-0.33
Acceleration Peak a_m (g)	200	204.81	-2.35
Head Injury Criterion HIC	627.5	655.5	-4.27

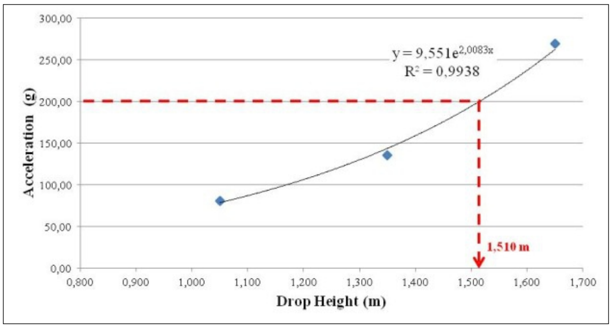


Fig. 7 Acceleration vs Drop height plot

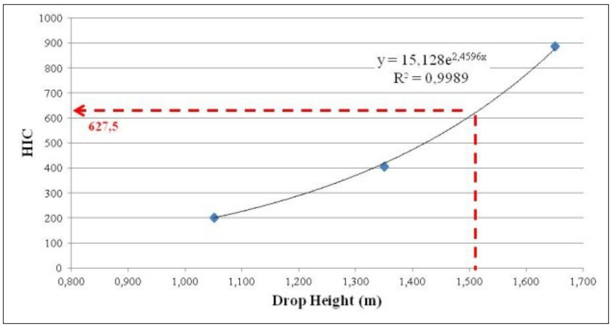


Fig. 8 HIC vs Drop height plot

4. Discussion

The main result obtained is that the critical heights following the EN 913 procedure are not safe. Following the EN 1177 procedure, having performed impact tests from drop heights equivalent to critical heights, greater than zero brain injuries probabilities were registered.

Therefore, the EN 913 acceleration performance criterion of 50 g does not take into account head injuries risk. This is a consequence of the different missile shapes. Due to a focusing of the initial impact loads on a small area, in fact, hemispherical-related acceleration peaks were always greater than the cylindrical ones. Many studies [19, 20] on low velocity impacts have confirmed missile shape influence on the mechanical behaviour of the material tested (in term of acceleration peaks, stress and absorbed energy responses).

On the other hand, the specifications in term of mass and circumference of the EN 1177 hemispherical missile agree with National Highway Traffic Safety Administration (NHTSA) pedestrian regulations [18, 21].

Further impact experiments were carried out and HIC scores related to acceleration peaks of 200 g are shown in Fig. 6: no architecture comply with the EN 1177 performance criterion of 1000 (HIC) when the acceleration response was equal to the life threatening threshold of 200 g established by Wayne State Tolerance Curve. Other impact testing experiments [22] on mat, padding and sport surfacing materials have confirmed that polymer-based foams exceed the acceleration limit of 200 g before the HIC limit of 1000 is reached. The opposite situation is detailed described to happen when impact tests are performed on fulfil materials like sand, wood chips and rubber [23].

Each impact testing series was also characterized by impact velocity measurement and related theoretical height calculation as post-processing: due to friction influence in the guidance system, measured drop heights were always greater than theoretical ones (Fig. 7) and drop height magnitude mainly appeared to contribute to the friction extent.

Finally, in order to declare a numerical variation between nominal and obtained impact testing outcomes (in terms of acceleration peaks, HIC, etc in Tab.6), a numerical procedure was implemented by fitting real measures (acceleration and HIC vs drop height plot in Figg. 8,9) using an exponential model. This model best fitted dynamic stresses (functionally related to acceleration peaks) and impact energies (functionally related to drop heights) real data, as showed for example in [24-26].

5. Conclusions

This paper aimed to define a special protocol useful to improve passive safety of protective devices actually installed in sports area. Several International standards, that provide impact testing procedure requirements, were analyzed and implemented in designing and building activity of a low-velocity impact testing apparatus. A special protocol was adopted during an experimental program carried out on several polymer-based foam architectures. Performance parameters were monitored in order to characterize architectures under test in term of impact attenuation properties. Performance criterions were finally took into account in order to comply Biomechanical recommendations and minimize potential brain injury risks of sports participants.

Previous results achieved by performing impact testing series have shown limitations in Sports area standard regulations and criterions concerning athletes passive safety.

According to biomechanical studies, life threatening brain injuries were pointed as the most relevant factor in order to improve impact testing procedure requirements. To this end, it has been shown how the severity of head impacts (in term of acceleration peaks) were underestimated when a cylindrical missile was used. On the other hand, an hemispherical missile, that best fits an anthropomorphic headform, was useful to introduce and evaluate potential of head injuries by assessing HIC parameter and its scores limit.

Furthermore, an acceleration and HIC variable (and respective performance criterion) joint monitoring is required when a proper brain injury risks assessment is meant to be took into account and sports protective devices limitations of use it is recommended to established.

Finally, in order to achieve impact testing protocol reproducibility and related results comparability between different laboratories on similar specimens, it is recommended to properly fix an interval tolerance for velocity measurements (by introducing friction influences and theoretical drop height parameter) and for acceleration measurements (by declaring a percentage variation between its nominal and measured values).

Authors are firmly convinced that it is recommended to define a new testing protocol through previous points practice that could allow technicians and sport safety responsible making right choices in impact attenuation properties evaluation and devices selection.

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In Verità,

non è stato un grandissimo momento per me, questo del dottorato. Mi aspettavo, forse, di trovare la strada. Verso un tesoro. Magari ho solo fatto esperienza per costruirne un contenitore. I preziosi, oggigiorno, latitano. E il lavoro di miniera fatto , alla fine, spesso non premia.

In Sincerità,

cos'è che oggi ha realmente valore?

In Realtà,

quello che ho frugato lungo questo sanguinante percorso, è tutto custodito in una piccola collezione di momenti impareggiabili. Disegnati amorevolmente da persone – ve lo consiglio con tutto me stesso – che bisognerebbe incontrare almeno una volta nella vita.

In Aggiunta,

le perle che ci sono sempre state, fino ad oggi, continuano ad illuminare questo mio cammino fatto di ansie e inquietudini. Ma quello che sono, lo devo soprattutto a voi.

In Sintesi e In Fine,

spero che il momento creativo, timidamente palesatosi –anni or sono - , ritorni. E mi devasti.

A tutti voi, schegge impazzite su questo mio pensieroso stagno, va un corale

GRAZIE

Alessio Max

Mamma

Stefan S. Maurizio Marya

Alida Carmine

Andrea Papà Fabrizio

Mariangela (stai pure qui?!) Tina Stephan K.

Ciro Giovanni Maria Rosaria

Giulia

Giuseppe Cristiano Vito

Claudio Nonna Gabriella Gianfranco