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

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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.

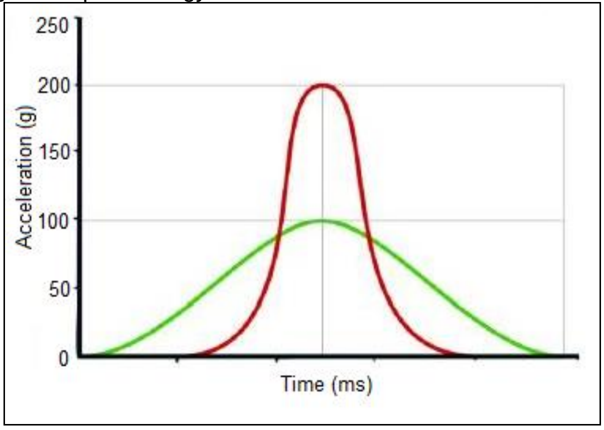


Fig. 1 Acceleration-Time trace for two different materials densities: soft surface (green line); hard surface (red line)

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.

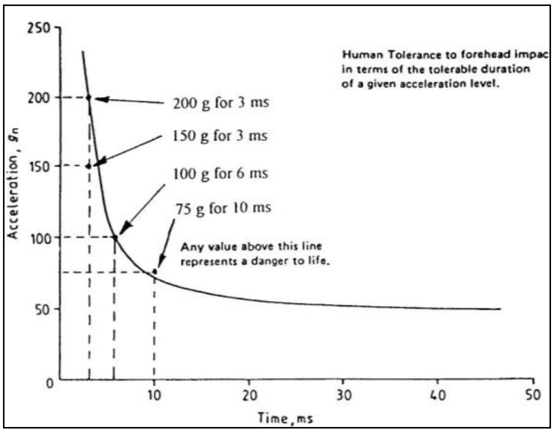


Fig. 2 Human tolerance to for head impact in terms of the tolerable duration of a given acceleration level [7]

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.

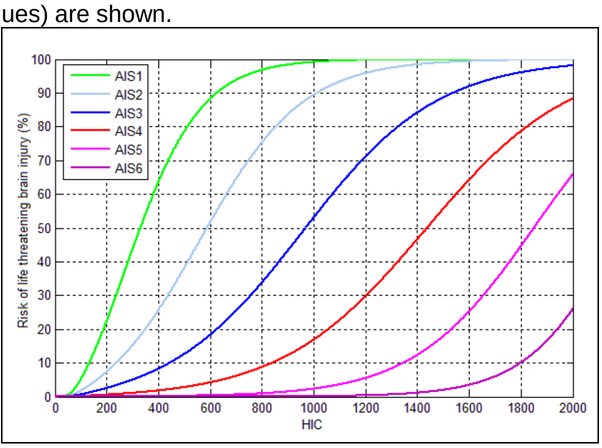


Fig. 3 Probability of Brain Injury vs HIC scores for AIS=1 to AIS=6 (minor injury to fatal injury)

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.

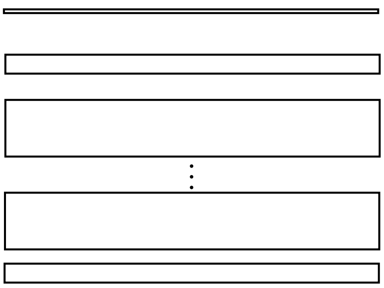
3 Materials and methods

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		Yes or Not
Top		Yes or Not
Core		Regular or Irregular
Down		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

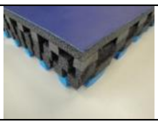
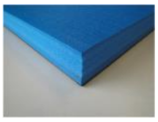
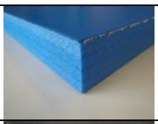
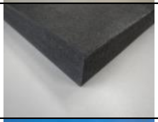
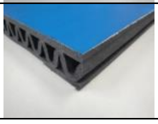
Tab. 1 Sandwich building scheme and material properties

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).

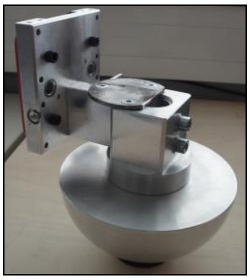


Fig. 4 Impact testing support assembly

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 (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 (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 (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 (v_{th}, h_{th}, r_v) were calculated in a post-process phase.

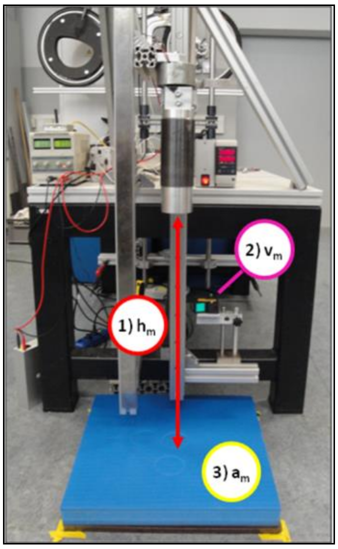


Fig. 5 Impact testing apparatus units

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

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 h_{cr} (maximum of 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.

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.

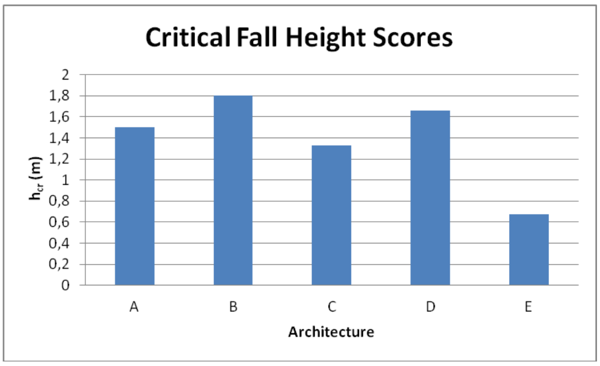


Fig. 6 Critical fall height Architecture performances

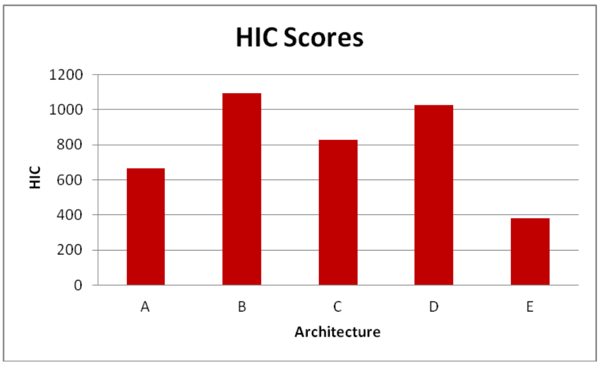


Fig. 7 HIC Architecture performances

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.

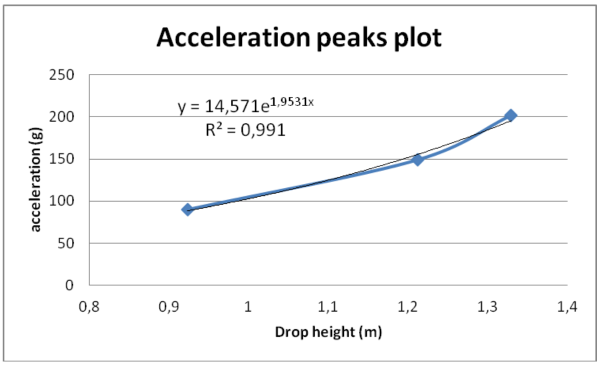


Fig. 8 Acceleration peaks vs drop height values plot

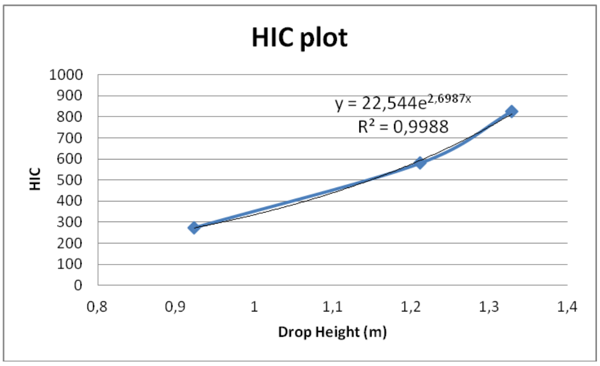


Fig. 9 HIC vs drop height values plot

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).

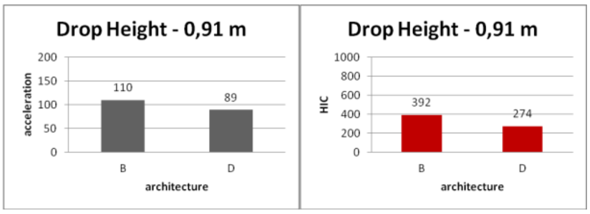


Fig. 10 Architecture B and D comparison in term of HIC and acceleration peaks performances from the same drop height 0.91 m

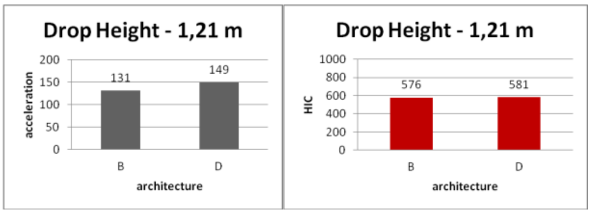


Fig. 11 Architecture B and D comparison in term of HIC and acceleration peaks performances from the same drop height 1.21 m

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].

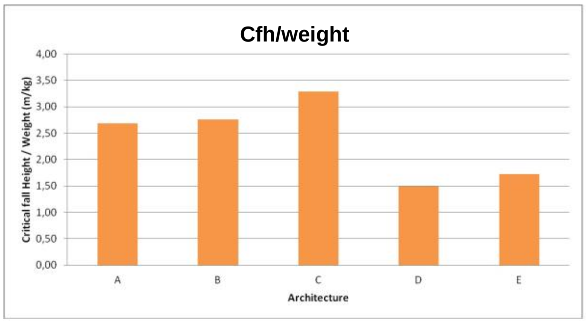


Fig. 12 Architecture performances in term of efficiency of use of the material

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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References

[1] European Parliament. Resolution of 2 February 2012 on the European Dimension in Sport 2011/2087 (INI), 2012.

[2] R. Bauer, M. Steiner. *Injuries in the European Union, Statistics summary 2005-2007*, Vienna: Kuratorium für Verkehrssicherheit, 2009.

[3] R. Kisser and R. Bauer. *The Burden of Sport Injuries in the European Union*. Research report D2h of the project Safety in Sports. Vienna: Kuratorium für Verkehrssicherheit, 2012.

[4] American Society for Testing and Materials. Standard specification for impact attenuation of surface systems under and around playground equipment, F1292–04. ASTM, 2004.

[5] European Committee for Standardization. Gymnastic equipment - General safety requirements and test methods, EN 913:2009. CEN, 2009.

[6] R. Willinger and D. Baumgartner, *Human head tolerance limits to specific injury mechanisms*, Int. J.Crash 8(6), pp. 605–617, 2003.

[7] C.Z. Cory, M.D. Jones, D.S. James, S. Leadbeatter, L.D.M. Nokes. The potential and limitations of utilising head impact injury models to assess the likelihood of significant head injury in infants after a fall. Forensic Science International 123 pp. 89-106, 2001.

[8] H.R. Lissner, M. Lebow, G. Evans. Experimental studies on the relation between acceleration and intracranial pressure changes in man. Surg. Gynec. Obst. U.S.A. 111, pp. 329-338, 1960.

[9] J. Versace. *A review of the severity index*, Vol. 710881. Ford Motor Co., pp. 771-796, 1971.

[10] P. Prasad and H.J. Mertz. The position of the United states delegation to the ISO working group 6 on(2)the use of HIC in the automotive environment. SAE Paper No. 851246, 1985.

[11] C. A. Hobbs and P. J. McDonough. *Development of the European new car assessment programme (Euro NCAP)*. Transport Research Laboratory. United Kindom, 1998.

[12] 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. September 19th -21th,2012, Capri, Italy, 2012.

[13] P.O. Sjoblom, T.J. Hartness, T.M. Cordell. On low-velocity impact testing of composite materials. Journal of Composite Materials,22 pp. 30-52, 1988.

[14] European Committee for Standardization.: Impact attenuating playground surfacing. :Determination of critical fall height, EN 1177:2008. CEN, 2008.

[15] American Society for Testing and Materials. Shock-Attenuation Characteristics of Protective Headgear for Football, F429–01. ASTM, 2001.

[16] G.F. Sushinsky. *Surfacing Materials for Indoor Play Areas – Impact Attenuation Test Report*. United States Of America Consumer Product safety Commission. CPSC, 2005.

[17] M. Prek. *Environmental impact and life cycle assessment of heating and air conditioning systems, a simplified case study*. Energy and Buildings 36 pp. 1021-1027, 2004.

[18] M. Patel, C. Bastioli, L. Marini, E. Wurdinger. *Environmental assessment of bio-based polymers and natural fibres* . Utrecht University - Department of Science,Technology and Society (STS); BIFA (Bavarian Institute of Applied Environmental Research and Technology), 2005.