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Toward a new approach for passive safety assessment of gymnastic equipment

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Materials

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.

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.

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.

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.

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: Engineering polymers; Design methods; Sport safety; Impact test

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1. Introduction

A recent study [1] 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.

At present the safety of protection devices in sports area is assessed according to sport safety standards associated with their specific use. In Table 1 a comparison among several international standards [2-7], 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 [8] it was investigated if the testing procedure given by European standard EN 913 [7] 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 [2]) and to correlate test results of the latter with EN 913.
In [9] 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

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 shown in experiments 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 portion of waveform (Fig. 1) to be measured during which HIC attains maximum value; 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=160 mm Mass=4.6 kg	Cylindrical Radius=64 mm Mass=9.1 kg	Hemispherical Radius=160 mm Mass=4.6 kg	Cylindrical Radius=64 mm Mass=9.1 kg	Hemispherical Radius=160 mm Mass=4.6 kg	Cylindrical Radius=75 mm 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}<200 g	HIC<1000 G_{max}<200 g	HIC<1000 G_{max}<200 g	G_{max}<200 g	HIC<1000	G_{max}<50 g

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.

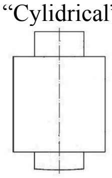
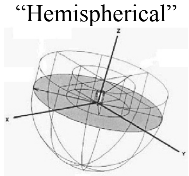
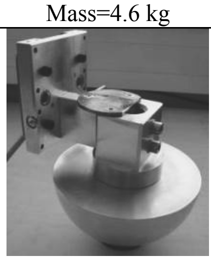
The potential for head injury had an influence on the development of sports protective devices and a shock attenuating surfaces evaluation began in 1975 when the US Consumer Product Safety Commission (CPSC) published its first hazard analysis and safety guidelines for playgrounds. In several cases, international 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 [8] was designed and built [16].

In order to carry out experiments during two different impact testing phases, the procedures that have been adopted referred to the EN 913 [7] and the EN 1177 [6] 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 Table 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.=75 mm Mass=8 kg	"Hemispherical"  Diam.=160 mm Mass=4.6 kg
Adopted Missile	 Mass=7991 g	 Mass=4623 g

According to single units apparatus descriptions [8] 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 (Acceleration Range: ±500 g; Sensitivity: 4 mV/g: Frequency Response: 10 to 25000 Hz) 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.

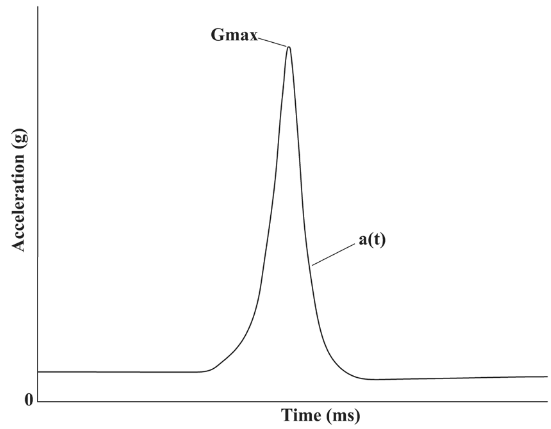


Fig. 1. Acceleration-Time curve

3.1. Materials

Specimens under test (50x50 cm) were structured in a sandwich mode [17] 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) [18,19], 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 Table 3) in four thickness categories (thin, intermediate, normal and thick) [20].

3.2. Impact testing procedures

Impact tests were performed through a flexible low-velocity impact testing apparatus [21] 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 [8], 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. From EN 1177 point of view, a similar procedure was adopted [9] through trial series of three consecutive impacts each, in order to establish the maximum drop height (named critical drop height) caused HIC scores lesser than the performance criterion of 1000. In addition, peak acceleration for each trial series was measured in order to assess the critical height related to the 200 g fatal injury threshold. All of the controlled (measured) and post-processed parameters are shown in Table 4.

Table 3.
Specimen architectures

Name	Photo	Layer number-density (kg/m^3)- Type	Thickness (mm)	Cover
A		1 - 30 - full 2 - 30 - cut 3 - 30 - cut	30	no
B		1 - 30 - full 2 - 30 - cut 3 - 30 - cut	31	yes
C		1 - 100 - full 2 - 30 - cut 3 - 30 - cut 4 - 100 - full	34	no
D		1 - 100 - full 2 - 30 - cut 3 - 30 - cut 4 - 100 - full	35	yes
E		1 - 60. - full 2 - 30 - cut 3 - 30 - cut 4 - 30 - cut 5 - 30 - cut	50	no
F		1 - 60 - full 2 - 30 - cut 3 - 30 - cu. 4 - 30 - cut 5 - 30 - cut	51	yes
G		1 - 100 - full 2 - 30 - cut 3 - 30 - cut 4 - 30 - cut 5 - 30 - cut 6 - 100 - full	54	no
H		1 - 100 - full 2 - 30 - cut 3 - 30 - cut 4 - 30 - cut 5 - 30 - cut 6 - 100 - full	55	yes

Afterward, in order to compare both of previous procedures parameters values, drop heights (h_{eq}) equivalent to EN 913 critical fall heights (h_{cr}) were calculated for EN 1177 procedure by equating impact energies [22-24] (functionally related to each missile masses) as following:

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

Finally, empirically equations for the evaluation of head injury trauma levels (AIS values) [15] were implemented in MATLAB software starting from input HIC scores:

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

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)

4. Results

Impact tests were performed on 8 architectures shown in Table 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 50 g.

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 Table 5).

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

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 Table 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 Table 5). Not significant probability that a fatal injury occurred was achieved for all of the architecture under test.

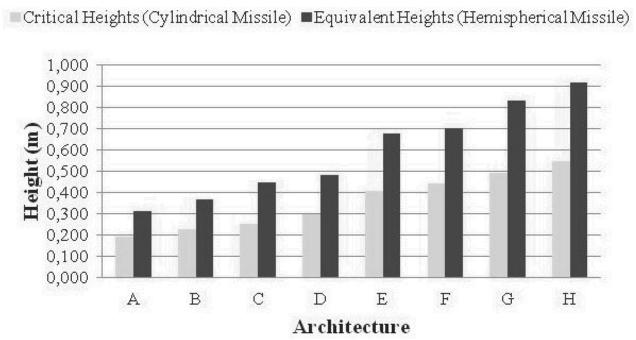


Fig. 3. Critical Heights (EN 913) compared to Equivalent Heights (EN 1177)

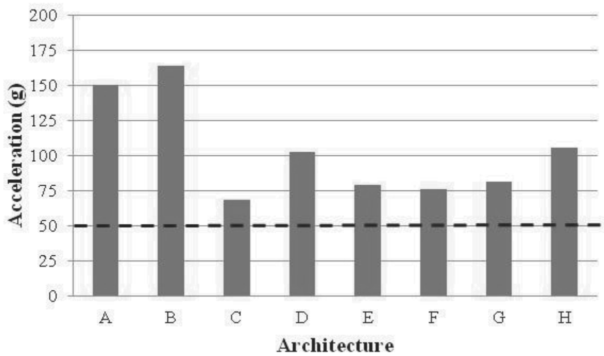


Fig. 4. Hemispherical Missile Accelerations measured from Equivalent Heights

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

During a second experimental 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.

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 200 g.

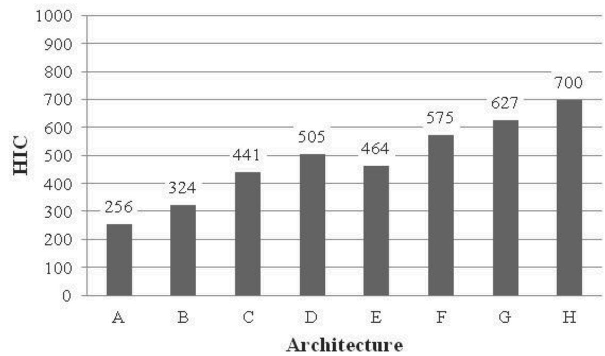


Fig. 5. HIC scores related to acceleration peaks ≈ 200 g

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

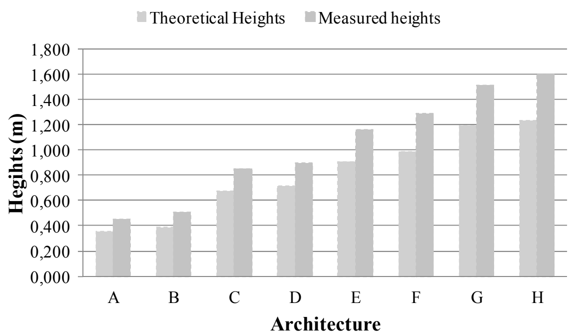


Fig. 6. Measured and Theoretical Drop Heights Comparison

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.

In Table 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

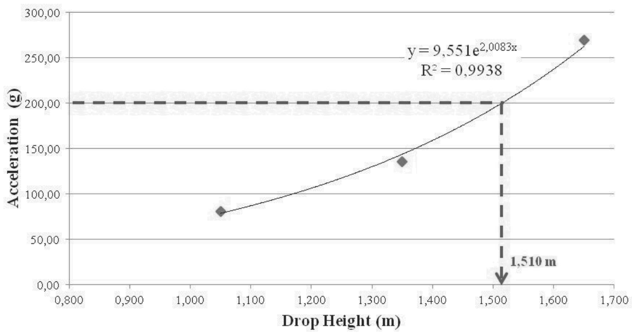


Fig. 7. Acceleration vs Drop height plot

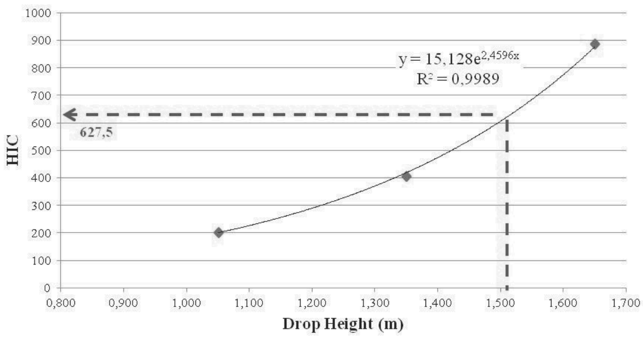


Fig. 8. HIC vs Drop height plot

5. 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 [26,27] 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 [25,28].

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 [29] 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 described in detail to happen when impact tests are performed on organic and inorganic loose fills like sand, wood chips and rubber [30].

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 Table 6), a numerical procedure was implemented by fitting real measures (acceleration and HIC vs drop height plot in Figs. 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 [31-33].

6. 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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