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New test method with a Hybrid III Anthropomorphic Dummy for Textile Safety Harnesses

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Abstract
A full body harness is a basic component of personal fall arrest equipment. It is made from webbing connected by seams and metal fittings to firmly hold and support the user's body. The paper proposes a new method for full body harness testing using a Hybrid III anthropomorphic dummy; also the design of the experimental stand and software used are described. The method analyses the behaviour of a dummy during a fall arrest under well-defined conditions. The critical mechanical factors measured during the study presented were: the head acceleration, forces acting on the spine, the position of the dummy, the impacts of harness elements to the head, etc. The tests identified some potentially dangerous phenomena associated with falls from a height. The harness testing method developed turned out to be a valuable tool that should be applied in conjunction with existing strength testing methods.

Key words: *full body harnesses, falls from height, anthropomorphic dummy, performance tests.*

Introduction

The use of personal fall arrest equipment is one of the most widespread methods of protecting workers who perform tasks at an elevated level. Fall arrest equipment is designed to address the most difficult challenge, that is, to save a person who is already falling. Such equipment is used in situations where one cannot eliminate the risk of falling due to the inherent characteristics of a job, for instance in the process of erecting steel structures. The equipment used under such conditions consists of three components:

- an anchor device attached to a structural element of the workplace [1],
- a shock-absorbing connecting assembly designed to safely absorb the kinetic energy of a falling user [2-6],
- a full body harness [7].

A full body harness is an element that remains in direct contact with the human body at all times. It is meant to:

- arrest the user's fall from a height,
- distribute the resulting dynamic forces across the most resilient body parts,
- appropriately position the human body during a fall arrest,
- make the user safe and reasonably comfortable when waiting for rescue after a fall arrest.

Industrial full body harnesses conforming to the standard PN-EN 361:2005 [7] are made of textile straps connected by means of seams and metal fittings to firmly hold and support the user's body. Sample full body harness types are shown in ***Figure 1***.

The most widespread full body harness designs consist of shoulder straps (6) crossing at the shoulder blade level. The shoulder straps are connected to or combined with thigh straps (7) depending on the harness type (variants A and B), forming loops around the thighs. In the gluteal region, the thigh straps may be connected by a sit strap (8). The harness straps are usually made of polyamide or polyester fibres. The minimum width is 40 mm for weight-bearing (primary) straps and 20 mm for secondary ones. In special use harnesses, e.g., where workers are at risk of molten metal splashes, the straps may be made of aramid or other highly durable fibres [8]. With a view to user comfort, the shoulder straps of some harnesses are made of elastic rubber-containing fabric, which does not restrain the user's movements, e.g., during bending. Depending on their design, full body harnesses are equipped with a variety of metal buckles and attachments, with the most important ones being dorsal (2) and chest (1) fall arrest attachments, as well as adjustment buckles (5) on the shoulder and thigh straps used to fit the harness to the user's body. Harnesses may also contain some plastic elements, such as loops and cross patches (for crossing straps). Full body harnesses may be equipped with attachments located near the user's center of gravity (3) for controlled lifting and lowering, as well as attachments (4) on the sides of the waist belt (9) for work positioning.

During a fall arrest, a full body harness is the decisive factor in protecting the user from injury or death. Its design, including the textile materials and metal fittings applied, must not create risks for humans, which should be verified in conformity tests. Such tests should assure that:

- the harness does not release the human body,
- the dynamic forces are distributed over the resilient parts of the human body,
- the user's position during and after a fall arrest is safe and does not lead to injury,
- elements of the harness do not pose a risk to the user, e.g., by impacting the user's body.

Since the existing methods for testing full body harnesses, based on standards harmonised with Regulation (EU) 2016/425 [9], cannot provide a full answer to the questions posed above, the current paper proposes a new test method involving an anthropomorphic dummy, and discusses the results obtained from a preliminary study.

The state of the art

Currently, full body harness tests verifying conformity with Regulation (EU) 2016/425 [9] are conducted in European laboratories according to the method given in the harmonised standards EN 361:2002 [7] and EN 364:1992 [10]. In that method, harnesses are tested using a rigid torso dummy, as specified in the standard EN 364:1992 [10]. The shape of the dummy is similar to the human torso; its mass is 100 kg and the center of gravity is 200 mm above the perineum. However, the mechanical parameters of

Figure 1. Sample full body harness types: 1 – chest fall arrest attachment, 2 – dorsal fall arrest attachment, 3 – abdominal fall arrest attachment, 4 – attachment for work positioning, 5 – adjustment buckle, 6 – shoulder strap, 7 – thigh strap, 8 – sit strap, 9 – belt for work positioning.

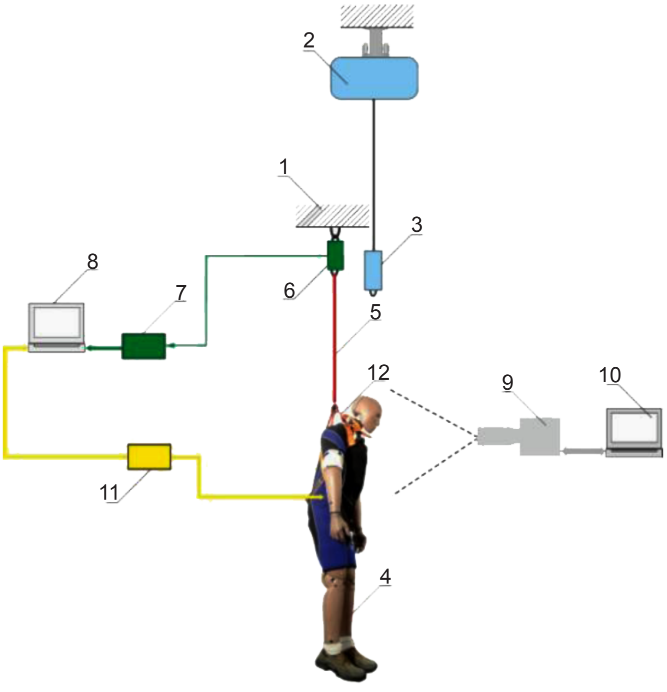

Figure 2. Experimental stand for testing personal fall arrest equipment with an anthropomorphic dummy: 1 – rigid beam, 2 – crane, 3 – electromagnetic latch, 4 – anthropomorphic dummy, 5 – test lanyard, 6 – force transducer at the anchor point, 7 – data acquisition system with an analogue filter and amplifier, 8 – computer, 9 – high-speed digital video camera, 10 – computer connected to the camera, 11 – interface between the dummy's data acquisition system and the computer, 12 – full body harness.

the torso dummy significantly deviate from those of the human body. Thus, the method involving the dummy is primarily suitable for strength testing (both under static and dynamic conditions). Its only features directly associated with fall arrests are releasing of the torso dummy and the angle between the dorsal plane of the torso dummy and the vertical following a fall arrest. In practice, the design of rigid dummies consistent with EN 364:1992 [10] does not allow for advanced studies of full body harnesses during a fall arrest.

Safety tests in the automotive, aviation, and space sectors involve anthropomorphic dummies which simulate the human body in tests entailing dynamic loading conditions. A good example of the development and improvement of anthropomorphic dummies is the "Hybrid" dummy in its successive iterations [11]. Of particular note is Hybrid III, which is used in human safety testing in a variety of fields of science and technology. Examples of the use of anthropomorphic dummies in tests involving mechanical vehicles and aircraft are given in [12-18] and [19], respectively. Anthropomorphic dummies are also very valuable tools in investigating the mechanical aspects of sports in which the human body is subjected to dynamic loads [20-23]. Works [24, 25] present methods for investigating the adverse factors acting on the human body during falls on flat surfaces.

Also the Hybrid II dummy was used in testing personal fall arrest equipment [26]. A study conducted at the BIA Institute in Germany concerned fall arrests in a vertical position, with the dummy not hitting any elements of the simulated work space. The study primarily focused on measuring head acceleration, the fall arrest force, and the pressure exerted by the harness straps on the dummy's body.

The results obtained from experiments involving anthropomorphic dummies must be in turn interpreted with certain evaluation criteria. Publications [27-30] define factors such as the maximum linear acceleration, the maximum linear acceleration with dwell times, the severity index (SI), the head injury criterion (HIC), angular acceleration (change in angular velocity), the generalised acceleration model for the brain injury threshold (GAMBIT), head impact power (HIP), the maximum chest deformation, etc. The above publications also provide data on the relationship between the levels of these parameters and the likelihood of injury to the user under dynamic loading conditions.

Methodology and experimental stand

The new methodology proposed evaluates the performance of full body harnesses and the behavior of an anthropomorphic dummy during a fall arrest conducted under well-defined conditions, as listed below:

- the harness is subjected to dynamic loads typical of fall arrest situations,
- the maximum force acting on the harness attachment approximates, but does not exceed, 6 kN, which is considered safe for humans [3],
- human users are simulated by means of a Hybrid III 50th Percentile Pedestrian anthropomorphic dummy from the company Humanetics [11],
- the crucial phenomena to be measured during a fall arrest include whether or not the harness releases the dummy, the spatial orientation of the dummy, unsafe displacements and deformations of harness elements on the dummy, impacts of harness elements to the dummy (especially to the head and neck), and other potentially harmful phenomena.

A preliminary study was conducted in accordance with the above methodology on an experimental stand schematically shown in ***Figure 2***.

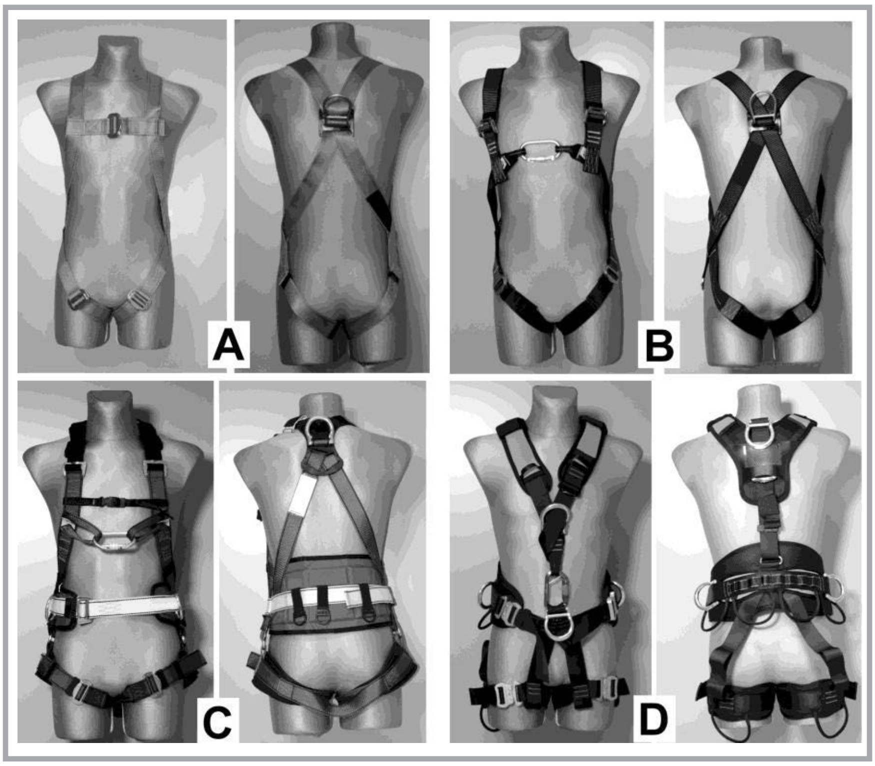

Figure 3. *Design variants of full body harnesses tested.*

Table 1. *Design of full body harnesses tested.*

Designation	Harness type (see *Figure 3*)	Harness elements
S1	A	dorsal fall arrest attachment secondary strap between the shoulder straps shoulder and thigh straps crossing on the hips adjustment buckles on the thigh straps and chest strap
S2	B	dorsal fall arrest attachment chest fall arrest attachment in the form of textile loops connected with a connector shoulder and thigh straps crossing on the hips adjustment buckles on the shoulder and thigh straps
S3	B	dorsal fall arrest attachment chest fall arrest attachment in the form of textile loops connected with a connector shoulder and thigh straps crossing on the hips adjustment buckles on the shoulder and thigh straps elastic shoulder straps
S4	C	dorsal fall arrest attachment chest fall arrest attachment in the form of textile loops connected with a connector thigh straps in the form of closed loops adjustment buckles on the shoulder, thigh, and hip straps hip strap with side attachments elastic shoulder straps
S5	D	dorsal, chest, and abdominal fall arrest attachments thigh straps in the form of closed loops adjustment buckles on the shoulder, thigh, and hip straps hip strap with side attachments

The basic component of the experimental stand is a Hybrid III 50th Percentile Pedestrian anthropomorphic dummy from the company Humanetics [11]. Its design (and especially the construction of its pelvis) makes it possible to place it in both upright and sitting positions, and thus it is suitable for fall arrest testing of full body harnesses. The dummy, weighing 78.15 kg, was developed based on anthropometric data for the 50th percentile of the American population. The dummy has triaxial accelerometers installed in the head, chest, and pelvis, as well as triaxial force and torque transducers located in the cervical and lumbar segments of the spine, force transducers in the thighs, arms, and forearms, and a transducer measuring chest deformation placed in the sternal region. These transducers are coupled to an internal data acquisition system, which is programmed prior to the test. After the test, the experimental data are transmitted from the internal memory bank of the dummy back to the computer (8) for further processing. During a fall arrest test, there is no wired connection between the dummy and the remaining part of the measurement setup. The fall arrest attachment of the full body harness (12) is connected to a 1 m long test lanyard (5) made of a dynamic climbing rope conforming to the standard EN 892:2012+A1:2016 [31]. The other end of the lanyard (5) is attached to a 9B-10kN force transducer (6) from Hottinger, which measures the fall arrest force acting at the anchor point located on the steel structure (1) complying with the standard EN 364:1992 [10]. The experimental stand is equipped with a crane (2) and electromagnetic latch (3), which holds the dummy. The jaws of the latch can be released by an electric signal, thus initiating a free fall of the dummy. The force transducer (6) is coupled

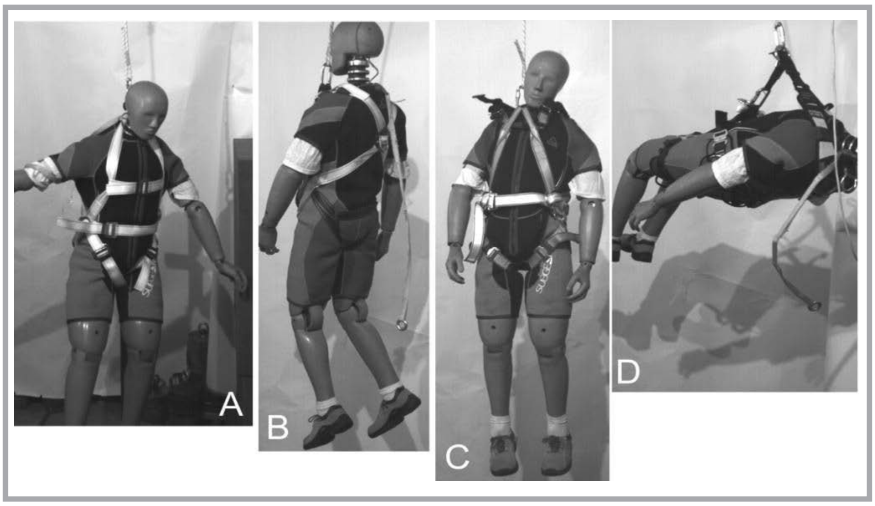

Figure 4. Examples of hazardous phenomena associated with the performance of a full body harness during a fall arrest.

to an MGA II amplifier from Hottinger, an MS210R/ET6 analog filter from IMD, a KUSB 3116 data acquisition system from Keithley Metrabyte (7), and a computer (8). The movement of the dummy and the performance of the harness during the fall arrest are recorded using a Cube 7 MotionBLITZ®EoSens high-speed digital video camera from Mikrotron GmbH (9) coupled to the computer (10).

In the method proposed, the anthropomorphic dummy is equipped with the full body harness tested of well-fitting size and a test lanyard [32]. It is lifted to a height by means of a crane (2), so that the distance of free fall amounts to $h = 1.0$ m. Under the circumstances, the maximum force acting on the fall arrest attachment of the harness ranges (4.0-6.0) kN, depending on the harness design and type of webbing used [33, 34]. The dummy may be suspended freely, or its feet may be supported on a beam simulating the edge of a work space. The movement of the dummy and the behaviour of the harness and its elements are recorded using a high-speed digital video camera (with the frame rate set to 2000 fps, based on preliminary results). The video material recorded is analysed using TemaMotion Starter II ver. 3.5 software [35] with object tracking technology to determine the displacement, velocity, and acceleration of selected points over successive video frames. The aforementioned mechanical forces acting on the anthropomorphic dummy were analysed using a program implemented in the Mathcad package [36].

Any impacts of harness elements to the dummy's head during the fall arrest can be identified by analysing the recorded video material and head acceleration curves. For instance, in this study a connector impact to the head was reflected by an abrupt surge in acceleration ranging from several *g* to several dozen *g*.

Table 2. *Test results for full body harnesses from experiments involving a Hybrid III 50th Pedestrian ATD anthropomorphic dummy.* ***Note:*** *No. – number of experiments for a given harness type, d – dorsal fall arrest attachment, c – chest fall arrest attachment.*

Harness	No.	Fall arrest attachment	F_{Amax}, kN	H_k, m	α, deg	a_x, g	a_y, g	a_z, g	F_{Nx}, N	F_{Ny}, N	F_{Nz}, N	Other phenomena identified
S1	1	d	5.61	0.170	16.9	-7.3	-1.1	-4.5	-278.9	50.6	-198.3	The shoulder straps tightened around the dummy's neck as the fall arrest attachment was displaced upwards (***Figure 4.a***).
	2		5.37	0.185	16.0	-6,4	0.5	-5.1	-294.1	-10.5	-203.4	
	3		5.80	0.192	13.7	-8.9	-2.3	-5.3	-298.6	25.7	-207.8	
S2	1	d	6.03	0.273	17.1	-8.1	-0.8	-4.2	-365.2	-26.6	-257.7	———
	2		5.98	0.256	15.4	-7.5	-0.3	-4.8	-381.2	-29.1	-262.1	
	3		6.10	0.284	15.0	-9.6	0.6	-5.0	-375.6	-20.0	-284.7	
	1	c	4.75	0.084	43.1	6.3	3.5	5.1	218.7	173.9	267.2	The connector hit the dummy's face as the chest fall arrest attachment moved upward (***Figure 4.b***).
	2		4.81	0.079	47.4	6.6	4.1	5.6	234.1	164.7	283.1	
	3		4.89	0.071	44.2	6.9	2.8	5.4	221.1	132.9	275.6	
S3	1	d	6.33	0.163	20.4	-10.8	-0.7	-5.1	-416.1	-23.4	-207.2	The shoulder straps tightened around the dummy's neck as the fall arrest attachment was displaced upwards.
	2		5.94	0.172	18.9	-13.1	0.4	-4.9	-428.6	-25.8	-212.7	
	3		6.11	0.158	18.3	-12.2	-0.8	-5.3	-432.7	-14.9	-231.3	
	1	c	5.20	———	89.9	-9.3	-3.1	8.1	-354.3	-119.0	369.1	The dummy's position was close to horizontal during the fall arrest.
	2		5.31	———	88.2	9.8	0.5	7.8	-362.1	-86.5	386.5	
	3		5.35	———	90.0	10.5	-2.3	9.2	-375.2	-63.4	379.9	
S4	1	d	5.13	0.090	47.5	-10.1	-2.6	5.0	-355.8	26.4	216.5	———
	2		5.17	0.085	44.6	-12.6	-1.6	4.8	-361.4	20.6	221.5	
	3		5.25	0.081	41.9	-14.3	-3.7	5.3	-365.9	27.0	230.4	
	1	c	4.17	0.144	72.4	-10.6	-3.5	-6.8	-942.9	-51.2	616.0	The connector hit the dummy's face. The dummy's position was close to horizontal during the fall arrest (***Figure 4.c***).
	2		4.28	0.120	69.1	-12.4	-2.1	-6.1	-1003.1	-23.9	654.1	
	3		4.36	0.112	67.2	-13.7	0.6	-7.3	-998.6	-37.1	671.2	
S5	1	d	5.42	0.212	22.3	-8.1	-0.4	-3.6	-337.5	-11.7	-165.2	The shoulder straps tightened around the dummy's neck as the fall arrest attachment was displaced upwards.
	2		5.78	0.190	20.5	-8.7	0.5	-4.1	-359.7	-24.6	-183.7	
	3		5.87	0.176	19.8	-7.5	0.7	-4.7	-399.1	-9.8	-191.2	
	1	c	4.33	——	88.9	-6.8	1.9	9.7	-260.9	79.0	435.7	The dummy's position was close to horizontal during the fall arrest (***Figure 4.d***).
	2		4.53	——	90.0	-7.5	0.6	10.2	-272.2	34.7	458.1	
	3		4.57	——	87.5	-7.9	-0.3	10.5	-291.3	45.1	471.2	

Full body harness testing

The method proposed was used in a preliminary study of five full body harness types, characterised in ***Table 1*** and ***Figure 3***.

Tests of each harness type were done in triplicate. Successive trials were carried out at intervals of at least 3 h to ensure relaxation of the objects tested. After each experiment, the harness was taken off the dummy, the adjustment buckles set in the initial position, and then the dummy was re-inserted into the harness. A new test lanyard was used in each experiment as the mechanical properties of that element were permanently altered by the dynamic load. The following parameters and phenomena were determined in each experiment:

F_{Amax} – maximum fall arrest force,
H_k – vertical displacement of the fall arrest attachment on the dummy,
α_{max} – maximum angle between the dorsal plane of the dummy and the vertical observed during a fall arrest,
a_x, a_y, a_z – maximum head acceleration measured in three orthogonal axes,
F_{Nx}, F_{Ny}, F_{Nz} – maximum forces acting on the upper part of the dummy's cervical spine measured in three orthogonal axes,
– other phenomena associated with the performance of the harness during a fall arrest.

The results obtained are presented in ***Table 2*** and ***Figure 4***.

Summary of test results

Summing up the test results, it may be concluded that:

- The maximum fall arrest force F_{Amax} ranged from (4.17-6.33) kN, which was close to the threshold specified in the European standards [3-6]. This also indicates that all the harness types tested had similar shock-absorbing properties.
- The greatest vertical displacement of the chest and dorsal fall arrest attachments reached approx. 0.3 m. In the case of the chest attachments, this resulted from the draping and stretching of the straps on the dummy. In turn, in the case of the dorsal attachment, this was attributable to the buckles sliding along the shoulder straps and the elongation of the textile material.
- The vertical displacement of the chest attachments created the risk of an impact to the dummy's head, which indeed was observed on several occasions.
- In some instances, the vertical displacement of the dorsal attachment decreased the horizontal distance between the shoulder straps, which tightened around the dummy's neck.
- The maximum head accelerations a_x, a_y, & a_z did not exceed the head injury thresholds [27-30].
- The maximum forces acting on the upper part of the cervical spine F_{Nx}, F_{Ny} & F_{Nz} did not exceed the spinal injury thresholds [27-30].

As a result of textile strap elongation and the straps sliding in the adjustment buckles, the angle α observed was approx. 90° in two cases, and approx. 70° in one case. Those instances, recorded for the chest attachment, are considered dangerous to the user pursuant to EN 361:2002 [7].

Conclusions

The new method of testing full body harnesses proposed can identify a number of hazardous phenomena associated with fall arrests that are not detectable by the existing test methods used for evaluating conformity with the standards harmonised with Regulation (EU) 2016/425 [9]. The most serious adverse events identified in the preliminary study include chest attachment elements hitting the head, shoulder straps tightening around the neck, and the human body adopting an unsafe position. These dangerous phenomena occurring during a fall arrest primarily result from textile strap elongation, the displacement of fall arrest attachments and adjustment buckles, and the harness design (inappropriate location of a fall arrest attachment with respect to the user's center of gravity).

Taking into account the importance of the effects on human health observed, it appears that the new method, involving an anthropomorphic dummy, is a valuable tool and should be performed alongside strength tests conducted pursuant to the standards EN 361:2002 [7] and EN 364:1992 [10]. The combined use of these two methods would more reliably detect unsafe full body harnesses and prevent them from being approved for use. Furthermore, in future studies the new methodology proposed will be expanded to include different positions of the dummy prior to the fall, simulating a variety of work conditions, such as falling head-first, tripping and falling from the edge of a work space, etc.

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References

1. European Committee for Standardization (CEN). (2012). Personal fall protection equipment – anchor devices (Standard No. EN 795:2012). Brussels, Belgium
2. European Committee for Standardization (CEN). (2010). Personal fall protection equipment. Lanyards (Standard No. EN 354:2010). Brussels, Belgium.
3. European Committee for Standardization (CEN). (2002). Personal protective equipment against falls from a height. Energy absorbers (Standard No. EN 355:2002). Brussels, Belgium.
4. European Committee for Standardization (CEN). (2002). Personal protective equipment against falls from a height. Retractable type fall arresters (Standard No. EN 360:2002). Brussels, Belgium.
5. European Committee for Standardization (CEN). (2014). Personal fall protection equipment. Guided type fall arresters including an anchor line. Guided type fall arresters including a rigid anchor line (Standard No. EN 353-1:2014). Brussels, Belgium.
6. European Committee for Standardization (CEN). (2002). Personal protective equipment against falls from a height. Guided type fall arresters including a flexible anchor line (Standard No. EN 353-2:2002). Brussels, Belgium.
7. European Committee for Standardization (CEN). (2002). Personal protective equipment against falls from a height – Full body harnesses (Standard No. EN 361:2002). Brussels, Belgium.
8. Baszczyński K, Jachowicz M. Load-Elongation Characteristics of Connecting and Shock-Absorbing Components of Personal Fall Arrest Systems. FIBRES & TEXTILES in Eastern Europe. 2012, 20, 6A(95):78-85.
9. Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC.
10. European Committee for Standardization (CEN). Personal protective equipment against falls from a height – Test methods (Standard No. EN 364:1992). Brussels, Belgium.
11. http://www.humaneticsatd.com/
12. Perz R. Metodyka badania podatności klatki piersiowej na obrażenia podczas

zderzenia czołowego. [Test method of chest susceptibility for injuries during head-on collision]. Prace Naukowe Politechniki Warszawskiej, Zeszyt 100, Transport, 2013. Politechnika Warszawska, Instytut Techniki Lotniczej i Mechaniki Stosowanej.

13. Jaśkiewicz M, Jurecki R, Więckowski D. Overview and analysis of dummies used for crash tests. Zeszyty Naukowe, Akademia Morska w Szczecinie, 2013, 35(107) s. 22-31.
14. Awrejcewicz J, Łuczak B. Calibration of the new human thorax model for low impact loading rates. *Journal of KONES Powertrain and Transport* 2007; 14, 1.
15. Viano D. C., Parenteau C. S., Burnett R.: Influence of Standing or Seated Pelvis on Dummy Responses in Rear Impacts. *Accident Analysis and Prevention* 2012; 45: 423-431.
16. Hu J, Klinich KD, Reed MP, Kokkolaras M, Rupp JD. Development and Validation of a Modified Hybrid-III Six-Year-Old Dummy Model for Simulating Submarining in Motor-Vehicle Crashes. *Medical Engineering & Physics* 2012; 34: 541-551.
17. Peng Y, Chen Y, Yang J, Otte D, Willinger R. A Study of Pedestrian and Bicyclist Exposure to Head Injury in Passenger Car Collisions Based on Accident Data and Simulations. *Safety Science* 2012; 50: 1749-1759.
18. Willinger R D. A Study of Pedestrian and Bicyclist Exposure to Head Injury in Passenger Car Collisions Based on Accident Data and Simulations. *Safety Science* 2012; 50 1749-1759.
19. Xiaochuan L, Jun G, Chunyu B, Xiasheng S, Rangke M. Drop Test and Crash Simulation of a Civil Airplane Fuselage Section. *Chinese Journal of Aeronautics* 2015; 28(2): 447-456.
20. Petrone N, Tamburlin L, Panizzolo F, Atzori B. Development of an Instrumented Anthropomorphic Dummy for the Study of Impacts and Falls in Skiing. *8th Conference of the International Sports Engineering Association (ISEA). Procedia Engineering* 2010; 2: 2587-2592.
21. Bartsch A, Benzel E, Miele V, Morr D, PrakashV. Hybrid III Anthropomorphic Test Device (ATD) Response to Head Impacts and Potential Implications for Athletic Headgear Testing. *Accident Analysis and Prevention* 48 (2012) 285-291.
22. Petrone N, Panizzolo F, Marcolin G. Behaviour of an Instrumented Anthropomorphic Dummy During Full Scale Drop Tests. 5th Asia-Pacific Congress on Sports Technology (APCST). *Procedia Engineering* 2011; 13: 304-309.
23. Miyamoto S, Inoue S. Reality and Risk of Contact-Type Head Injuries Related to Bicycle-Mounted Child Seats. *Journal of Safety Research* 2010; 41: 501-505.
24. Deemer E, Gina Bertocci G, Pierce MC, Aguel F, Janosky J, Vogeley E. Influence of Wet Surfaces and Fall Height on Pediatric Injury Risk in Feet-First Free Falls as Predicted Using a Test Dummy. *Medical Engineering & Physics* 2005; 27: 31-39.
25. Raymond D E, Catena R D, Vaughan T R. Biomechanics and Injury Risk. Assessment of Falls onto Protective Floor Mats. *Rehabilitation Nursing*, 2011; 36, 6, November/December: 248-54.
26. Kloß G, Ottersbach HJ. Aufbau von Versuchseinrichtungen für Fallversuche mit einem Gliederdummy. Abschlußbericht Nr. 8907112.2 zum Projekt nr. 6042. Fachausschuß Persönliche Schutzausrüstung, Kronprinzenstraße 62-67, 44135 Dortmund 1.
27. Nelson J K Jr, Waught P J, Schweickhardt A J. Injury criteria of the IMO and the Hybrid III dummy as indicators of injury. *Ocean Engng* 1996; 23, 5: 385-401. Copyright © 1996 Elsevier Science Ltd.
28. Marjoux D, Baumgartner D, Deck C, Willinger R. Head Injury Prediction Capability of the HIC, HIP, Simon and ULP Criteria. *Accident Analysis and Prevention* 2008; 40: 1135-1148.
29. Hutchinson J, Kaiser M J, Lankarani H M. The Head Injury Criterion (HIC) functional. *Applied Mathematics and Computation* 1998; 96: 1-16.
30. Newman J, Barr C, Beusenberg M, Fournier E, Shewchenko N, Welbourne E, Withnall C. A New Biomechanical Assessment of Mild Traumatic Brain Injury. Part 2: Results and Conclusions. Proceedings of the 2000 International IRCOBI Conference on the Biomechanics of Impact 2000; September 20-22, Montpellier, France.
31. European Committee for Standardization (CEN). (2016). Mountaineering equipment. Dynamic mountaineering ropes. Safety requirements and test methods (Standard No. EN 892:2012+A1:2016). Brussels, Belgium.
32. Baszczyński K, Jachowicz M. Load-Elongation Characteristics of Connecting and Shock-Absorbing Components of Personal Fall Arrest Systems. *FIBRES & TEXTILES in Eastern Europe* 2012, 20, 6A(95): 78-85.
33. Baszczyński K. Modeling the Performance of Selected Textile Elements of Personal Protective Equipment Protecting against Falls from a Height During Fall Arrest. *FIBRES & TEXTILES in Eastern Europe* 2013, 21, 4(100): 130-136.
34. Baszczyński K. Modeling the Performance of Horizontal Anchor Lines During Fall Arrest. *FIBRES & TEXTILES in Eastern Europe* 2017; 25, 5(125): 95-103. DOI: 10.5604/01.3001.0010.4634http://www.imagesystems.se/image-systems-motion-analysis/products/tema-motion.aspx.
35. https://www.ptc.com/en/products/mathcad.

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