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Procedia Engineering 2 (2010) 2593–2598

Procedia Engineering

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8th Conference of the International Sports Engineering Association (ISEA)

Full scale impact testing of ski safety barriers using an instrumented anthropomorphic dummy

Nicola Petrone[a,*], Francesca Ceolin[b], Tommaso Morandin[b]

[a]*Department of Mechanical Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy*
[b]*DolomitiCert Laboratories, Longarone BL, Italy*

Received 31 January 2010; revised 7 March 2010; accepted 21 March 2010

Abstract

The results of full scale testing on type A nets and mattresses are reported. Tests were performed by using an anthropomorphic dummy wearing boots, skis and helmets, developed for the scope. The tests were performed in the field by means of a tower pendulum of 18 m height. Maximum impact speed was 66 km/hr: head and chest deceleration values measured by means of tri-axial accelerometers were evaluated together with high speed video taken from the top of the impact area. The method can be applied for the validation of safety barriers in skiing and for the evaluation of protective equipments.

Keywords: Skiing; safety barriers; impact tests, antrhropomorphic dummy

1. Introduction

Skiing injuries are mostly related to personal falls during slalom or collisions with other skiers and snowboarders: fixed obstacles collisions are seldom occurring, but the consequences can be very severe.

This is even more important in competitions where type A (nets of 4m height or more, made of 5mm polyethylene plait, mesh of 50x50 mm, supported by steel poles and perimetral cables) and B nets (nets of 2m height made of 3,5 mm polyethylene plait, mesh of 50x50 mm, supported by PVC poles) are placed in front of rocks or trees together with foam and air mats to ensure the proper degree of safety without disturbing the visibility of the race event.

Despite the importance of such safety barriers, there are neither standards nor regulations available regarding the crashworthiness of such equipment.

The present work was developed within the INTERREG IV project SkiProTech, in order to develop sound test methods for reproducing impacts of instrumented anthropomorphic dummy against safety barriers or obstacles under controlled conditions.

* Corresponding author. Tel.: +39-049-8276761; fax: +39-049-8276785.
E-mail address: nicola.petrone@unipd.it

1877-7058 © 2010 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2010.04.037

In some previous studies, two methods for launching a solid cylindrical dummy against barriers were evaluated; a tower pendulum [1] and a snow toboggan [2], allowing to measure high impact decelerations.

In this work, some limitations of the previous experiences were overcome: (i) an anthropomorphic dummy wearing boots and skis was used for comparison with a solid cylindrical dummy, (ii) the tower pendulum was raised from 12m to 18m to increase the impact speed, (iii) the dummy was released from the suspension cable in the instants prior to the impact so that its behaviour was unrestrained, (iv) a high speed camera was placed over the collision area to film the events at 350 fps.

2. Instrumentation

The impact tests were performed using two different dummies instrumented with triaxial accelerometers.

A solid wooden dummy (named "DummyS0") of 75 kg was used as in a previous experience to find direct correlation with former available data [1]. In addition to that, an anthropomorphic dummy, intentionally developed for the project, was used in the impact tests [3]. The anthropomorphic dummy, named "DummyA1", was specifically developed in order to fulfill the following minimum requirements: (i) presence of a realistic head & neck assembly to wear helmet and neck protectors, (ii) presence of suitable flexible feet enabling to wear boots and skis, (iii) presence of flexible knees to introduce a possible knee compliance during the impacts.

The DummyA1 was obtained by assembling a Hybrid II neck/head assembly to a solid wooden trunk: two customize legs, including a flexible knee and a silicon dummy foot, were developed and applied to the wooden thigh proximal portions as shown in Fig. 1.a. The total mass of the dummy with boots was 85 kg.

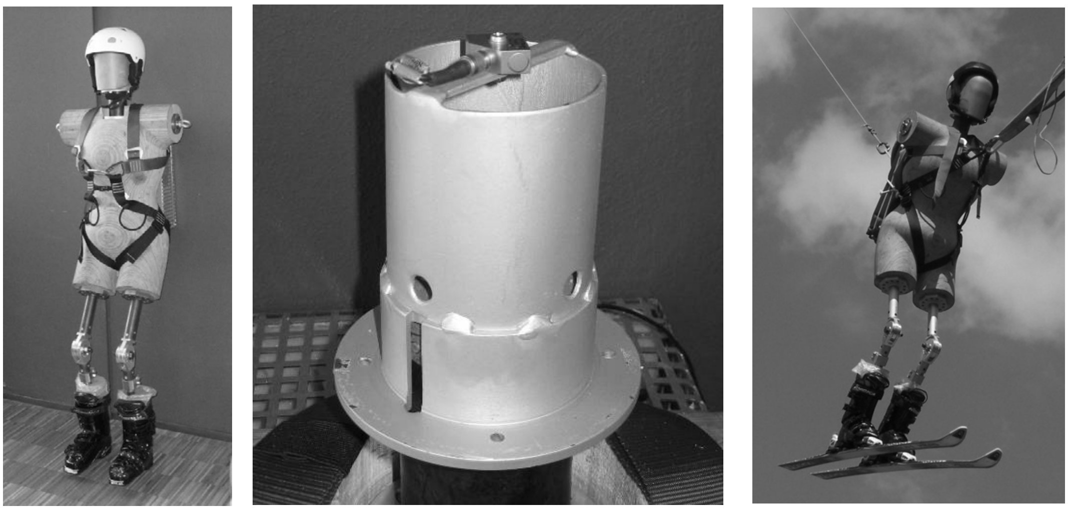

Fig. 1. (a) Complete DummyA1. (b) Accelerometer support at the head COM .(c) Dummy A1 wearing boots and skis ready for the impact tests.

Triaxial accelerometers were applied to the trunk center of mass and the head center of mass: ICP accelerometers had a full scale of 500g, a -3 dB range of 30 kHz and were connected to a IMC Cronos data acquisition system, controlled by a Laptop, that enabled a sampling rate of 50 kHz per channel. The reference system of the accelerometers was defined as follows: X axis in the lateral right direction, Y axis parallel to the suspension cable, positive upwards, Z axis parallel to the impact direction, positive backwards.

Signals from the accelerometers were transmitted to the data acquisition system by means of cables climbing up to the suspension tower and coming down to the control desk. A KMT 8 channel telemetric system was evaluated during pilot tests but not used during real tests due to its unknown crashworthiness. A protective steel cage was placed as a back pack on the dummy to contain the cable connections and the telemetry system.

The testing ground was established in a skiing area in San Vito (BL-Italy), where type A nets were supposed to be placed in winter to protect from the trees. Two girder towers of 18 m length were placed on the ground (Fig. 2): on the tip of the suspension tower, a steel cable was fixed to sustain the dummy during the flight phase. The dummy, wearing a climbing harness, was suspended approximately at the chest's center of mass. The second tower was sustaining a lift cable, activated from the ground and fixed to the dummy's pelvis, with the function of lifting the dummy up to a maximum drop height of 18 m.

A special karabiner was applied to the dummy harness in order to obtain the dummy release at the instant of impact: the karabiner could be opened by a trigger cable tuned to release when the dummy was hitting the barrier.

The impacts were filmed by four commercial digital cameras filming at 50 fps (Side, Rear Right, Rear Left, Behind the nets); a high speed camera MotionBlitz was placed right at the top of the impact area and lifted by a crane.

The net specimens used during the tests were type A brand new nets as used in the ski competitions (4m height, 50x50mm net, 5 mm diameter). Two A-nets at a distance of 0.8 m were sustained by steel cables (7m height) and pulleys spaced of 2.2 m (Fig. 3.a). The installation was carried out by expert operators applying state of the art materials under the supervision of a FIS safety officer. As in the competitions, a gliding sheet was applied to the lower part of the first net. The tests configuration with all nets and sheet were therefore indicated as "SC/A1/A2"; tests without the rear nets were indicated as "SC/A1" and those without the gliding sheet were named "A1".

Also foam mattresses as those used in the skiing world cup and tested in the previous studies [1,2] were used: they are based on an innovative modular system of 2.5x1.3x0.40 m dimensions, covered with PVC sheets and stitched by cables. The mats can be composed by two opposed halves based on a square-wave profile that can be faced and piled up to give greater energy absorption thickness. Three halves were used to obtain a 1.5 configuration (Fig. 3.b).

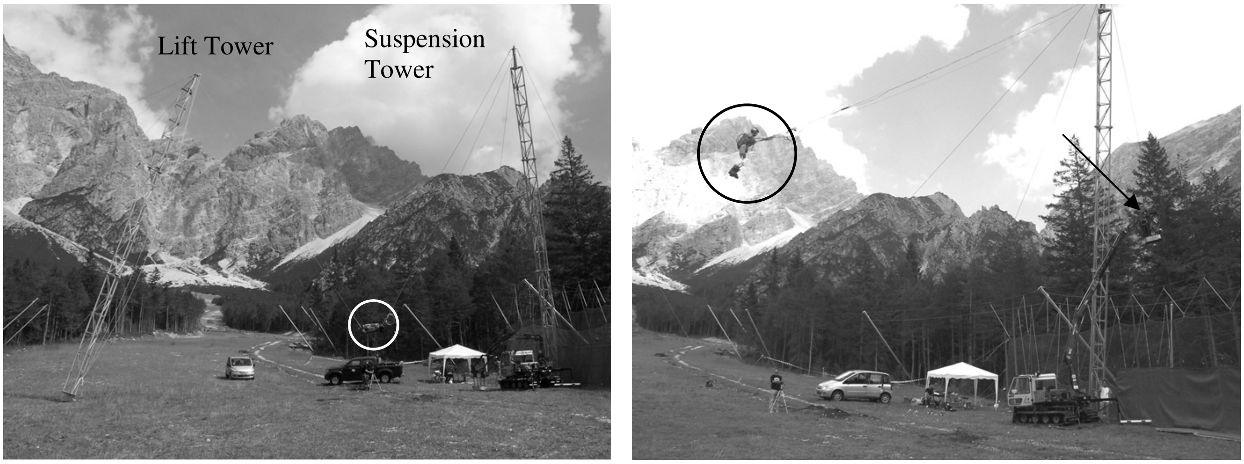

Fig. 2. (a) Overall view of the testing ground, with the barriers under testing on the right, below the suspension tower, and the lift tower on the left. The DummyS0 is highlighted by the circle. (b) View of type A nets barriers under testing, the suspension tower, the DummyA1 (highlighted by the circle) and the High Speed camera operator lifted over the nets by a crane (arrow).

3. Methods

The tests were performed initially with the solid dummy, in order to obtain data comparable with previous tests and to check the overall arrangement of towers, barriers, cameras, release devices within high levels of safety for the operators and the instrumentation. In a second stage, the tests were performed with the anthropomorphic DummyA1, and several tests were performed without skis and with skis, on nets and foam mats. A total number of 30 impacts were performed in two days of tests in summer 2009. The suspension cable was regulated in order to obtain the ski/boot impact at approximately 0,5 m from the ground.

The impact speed was calculated by photocells and confirmed by analysis of high speed video from the top. The accelerometers signals at head and chest were low-pass filtered with a cutoff frequency of 1000 Hz and analyzed to calculate the instantaneous resultant accelerations (vector sign corresponding to the sign of the components of highest magnitude). The Head Injury Criterion with 15 ms window (HIC 15, as defined in (1)) was adopted as a general safety criterion at the head for this type of impact.

$$HIC_{15} = sup_{t_1 t_2} \left\{ \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \cdot dt \right)^{2.5} (t_2 - t_1) \right\} \quad (1)$$

where $a = \sqrt{a_x^2 + a_y^2 + a_z^2}$ and $(t_2 - t_1) = 15ms$.

The depth of maximum penetration of the dummy in the barrier was estimated by analysis of frames collected by the high speed camera from the top view, after scaling the dynamic images to reference dimensions placed on the ground.

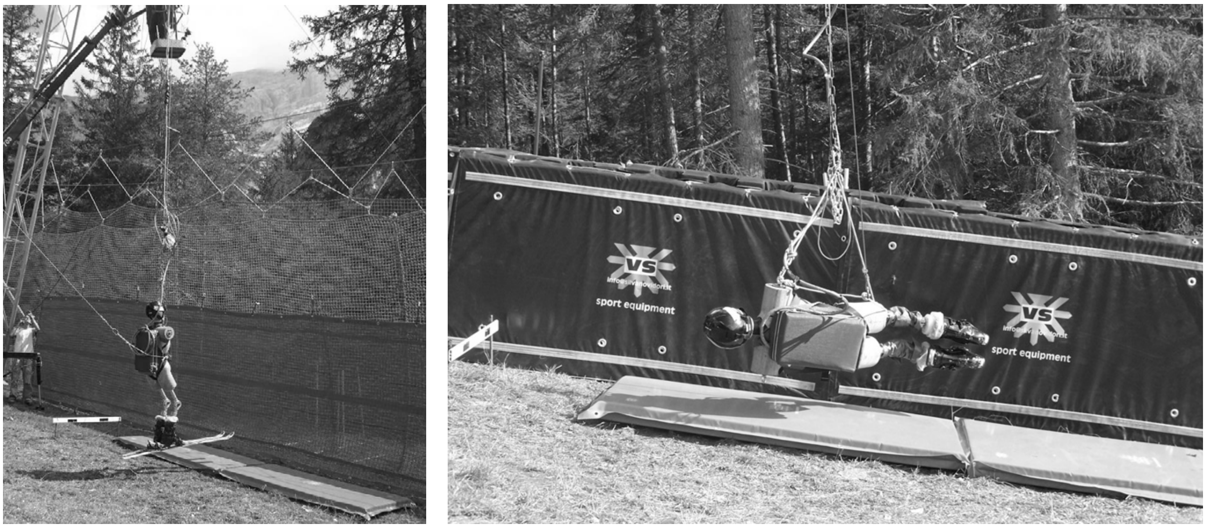

Fig.3. (a) Nets type A undergoing the test: the gliding sheet is applied to the first A1 net and the second A2 net is 1.5 m behind. (b) Foam mattresses undergoing impact tests.

4. Results

The results of valid impact tests performed on safety barriers with DummyA1 are summarized in Table 1. Together with the reference test number, the type of barrier and the type of skis (with binding preloading) are listed. The impact speeds, as the speed estimated prior to the first contact with the barrier, are also listed: in some cases, low values of impact speed were obtained due to the anticipated impact of skis tips or boots with the ground.

A fundamental set of results is the list of depth of penetration reached by the dummy during the impacts: highest penetration of 1850 mm (bold in the Table) was recorded during Test 20 (two nets with gliding sheet) at 63 km/h with no damage to the nets. A high penetration was obtained also on a single net A1 after the skis had cut the net in Test 24 (Fig. 4.b). The other columns collect the recorded values of head & chest resultant accelerations. At the head, the HIC15 computed on the resultant acceleration is also reported (usual injury limit value is around 1000).

Examples of frames recorded during the impacts are reported in Fig. 4. The impressive bending of skis before release (no damage to the skis), the skis entrapped in the cut net and the extreme backward neck flexion during the impact on foam mattresses can be estimated from the picture.

Table 1. Results of impact tests with DummyA1. The SPEED of impact and the penetration DEPTH of the dummy in the barriers are reported. The Maximum and Minimum values of the resultant Accelerations at the head and the chest are reported. For the head, the maximum recorded values for the HIC_{15} criterion calculated with formula (1) are also reported.

					HEAD ACCELERATION RESULTANT $\mathbf{a_H}$			CHEST RESULTANT $\mathbf{a_C}$	
TEST NR.	**BARRIER**	**SKIS**	**SPEED [km/h]**	**DEPTH [mm]**	**MAX [g]**	**MIN [g]**	**HIC**	**MAX [g]**	**MIN [g]**
12	Nets SC / A1 / A2*	NO	50	1350	71,12	-43,15	143,84	13,91	-10,52
13	Nets SC / A1 / A2	NO	63	1500	73,75	**-169,11**	302,59	16,60	-35,68
14	Nets SC / A1 / A2	NO	60	1400	69,36	-84,96	116,62	14,69	-11,92
16	Nets SC / A1 / A2	NO	60	1300	64,85	-31,94	143,51	7,80	-6,26
17	Nets SC / A1 / A2*	L 170cm; 6 DIN	47	1250	54,30	-19,57	53,06	5,37	-4,63
18	Nets SC / A1 / A2#	L 170cm; 6 DIN	57	1700	142,94	-104,48	129,36	17,91	-8,00
19	Nets SC / A1 / A2*	L 198cm; 10DIN	33	1200	**189,23**	-60,82	182,39	15,12	-52,68
20	Nets SC / A1 / A2	L 198cm; 10DIN	63	**1850**	78,63	-44,84	111,3	8,25	-9,83
21	Nets SC / A1	NO	63	1400	65,60	-20,33	121,7	24,70	-12,15
22	Nets SC / A1	L 198cm; 10DIN	62	1650	171,52	-32,17	143,4	18,87	-36,41
23	Net A1	NO	61	1500	52,15	-21,22	123,7	19,15	-14,73
24	Net A1 § #	L 165; 10 DIN	63	1800	47,56	-15,47	146,2	14,09	-5,68
26	Foam Mat 1.5	NO	61	904	161,15	-88,37	**571,1**	24,30	-39,44
27	Foam Mat 1.5	NO	60	780	168,34	-40,10	137,7	15,11	-30,24
28	Foam Mat 1.5	NO	**66**	1285	166,63	-64,69	239,2	19,17	**-81,90**
29	Foam Mat 1.5 °	L 165; 10 DIN	59	1030	185,79	-145,12	1869,9	**28,79**	-59,67
30	Foam Mat 1	NO	63	1120	78,95	-13,16	170,6	17,13	-14,87

NOTES: * Dummy contacts the ground before the impact. § Net failure. # Ski Failure °Head impacting rearward with the back cage.

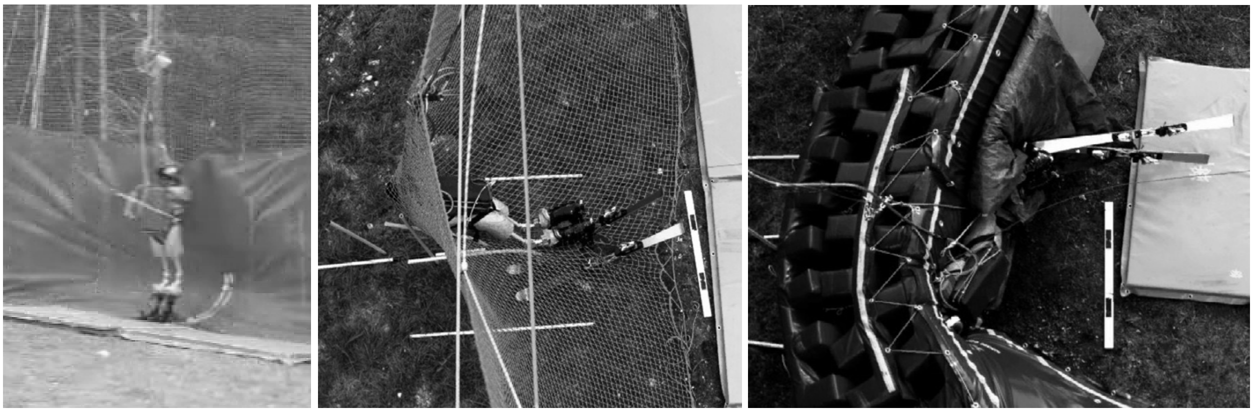

Fig.4. (a) Test Nr.22. Impact of DummyA1 wearing long skis against the SC/A1 nets: notice the extreme ski bending before binding release. (b) Test Nr.24. Impact of DummyA1 wearing short skis against the A1 net at maximum penetration depth. (c) Test Nr.29. Impact of DummyA1 wearing skis against the 1.5 foam mats at maximum penetration depth.

5. Discussion

The aim of the work was the overcoming of major limitations presented by former studies in the development of a standard method for the dynamic evaluation of crashworthiness of safety barriers, mostly used in ski competitions and recreational ski areas.

The use of the anthropomorphic dummy instead of a solid cylindrical dummy, despite its complexity, enhanced the significance of the tests allowing the introduction of such long and sharps equipments as the skis are. The impact speed was generally raised after the adoption of 18m long towers instead of the 12 m towers used in previous tests: the speed values lower than theoretical can be justified by the high aerodynamic drag of DummyA1 versus dummy D0.

The introduction of a release system in the suspension cable was successfully tested and allowed to obtain more realistic trajectories of the dummy during the impact and the bouncing back stage.

In addition, the impact kinematics was clearly filmed via the top high speed camera, enabling to follow the mechanics of head impact and neck extension, skis bending and binding release instants, net tensioning and foam mattresses indentation.

In terms of recorded values, the results collected in Table 1 show that it is difficult to obtain consistent values on all parameters during repeated tests on the same specimens and with the same conditions (example, tests Nr. 13,14,16, or Nr. 26,27,28), so that the evaluation of mean values seems not meaningful: this is due to the complexity of the phenomenon. The use of a solid dummy against barriers as in [1] was giving more repeatable results: nevertheless, the results from Table 1 have to be considered useful in the evaluation of peak values, in the research of maximum values obtained with test conditions more realistic than in [1].

Several failures of ski shovels, ski bindings, boot clips, helmet straps, type A nets and mattresses cover sheet were recorded: this gave interesting information to equipment manufacturers in such extreme events. The method resulted to be appropriate for a full scale evaluation of protective devices like helmets, neck braces, knee braces and back protectors.

The most important information was the evaluation of the amount of deepest penetration of the dummy in the net, to be used as a start requirement for the correct placement of nets ahead of rocks or trees.

Acknowledgements

The authors intend to thank the Vidori Sport Equipment – S. Vito (BL-Italy) for supporting the field testing of safety barriers.

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