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Padding performance according to impact conditions and cycle of use in ski areas



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ABSTRACT

Objective: Collisions with obstacles are among the most severe accidents recorded in ski areas. In France, the padding placed on these obstacles conforms to a design standard to assess its ability to dissipate energy when impacted by a skier/snowboarder. Padding performance, i.e. its ability to prevent or mitigate injuries and the changes in performance over time remain poorly understood. Considering the global objective to explore the padding's ability to protect from injuries during its cycle of use, a large experimental campaign was designed to investigate various padding performance.

Design: Experimental drop tests were performed on padding in ski areas using instrumented head and trunk impactors.

Method: The influences of the padding's properties (thickness, age, impact location, cover), environment (temperature, position on the obstacle) and impact conditions (speed, impactor) on head and chest accelerations were investigated. 180 drop tests were performed on 40 padding samples (with thicknesses ranging from 10 cm to 30 cm) with ages varying from 0 to 17 years old.

Results: This study showed a significant influence of speed, impactor and the padding's thickness ($P < 0.001$) and also position. However, temperature, aging, impact location and cover type did not have a clear influence on impact accelerations for these impact conditions.

Conclusions: This study is an innovative step towards a better understanding of ski padding performance and behavior. These results provide quantitative information for the development of best practices aiming at ski areas increasing safety on their slopes. They also highlight challenges and perspectives for the design of future padding.

1. Introduction

Collisions with fixed obstacles (CWOs) are among the most severe accidents recorded in ski areas, with 48% of moderate to severe traumatic brain injuries being caused by this mechanism [1]. Head and trunk are injured in 40% of CWOs [2] and should be the primary concern of CWO protection. The head and trunk have also been shown to impact the obstacle with high normal impact speeds (head: 30 ± 15 km/h, trunk: 24 ± 15 km/h) [3]. To reduce the severity of CWOs, ski areas attach dedicated ski padding to the obstacle. The few studies investigating ski padding performance have highlighted the influence of padding thickness and impact speed on linear head accelerations [4–6]. However, the studies were either conducted on a reduced sample of padding [6], at

moderate impact speed (15 km/h) [5], or on thick, competition-grade padding [4].

Currently, there is only one published standard that imposes performance specifications for ski padding under impact conditions. According to this standard, which is written in French, the padding is evaluated flat on the ground, at room temperature, using a hemispherical mass (diameter: 15 cm, 30 kg, 100 J, 9.3 km/h) and a flat impactor (diameter: 20 cm, 30 kg, 440 J, 19.5 km/h) [7]. These conditions are not representative of head or trunk impact conditions [3], nor of the padding found on ski slopes (temperature, position). Padding performance in real-life conditions remains unknown in terms of the influence of the impacting object (speed, mass, shape), the outside environment (temperature, fastening on obstacle) and the padding itself (thickness, age, cover type).

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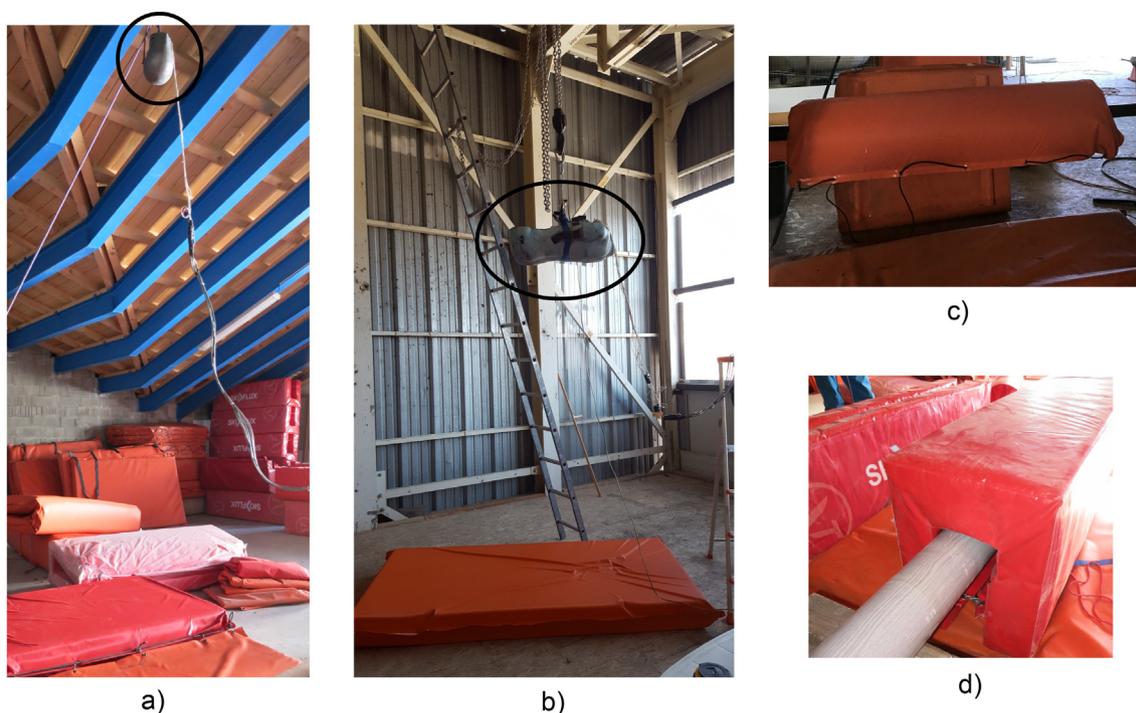


Fig. 1. Experimental drop tests on flat padding on the floor with a) the headform, b) with the trunk, c) on cylindrical padding placed on a pole (diameter of 9-cm) and d) on a 3-parts shape padding placed on a pole (diameter of 16-cm).

Table 1

Description of the padding impacted and tests.

Padding thickness	10 cm	15 cm	20 cm	30 cm	Total
Main study: head impacts on flat padding on floor					
Number of padding samples impacted	3	17	8	4	32
Number of tests at 2 m	6	34	16	8	64
Number of tests at 3 m	2	34	16	8	60
Complementary study: trunk impacts on flat padding on floor					
Number of padding samples impacted	/	3	2	1	6
Number of tests at 2 m	/	6	4	2	12
Number of tests at 3 m	/	6	4	2	12
Complementary study: head impacts on cylindrical padding on obstacle					
Number of padding samples impacted	/	8	/	/	8
Number of tests at 2 m	/	16	/	/	16
Number of tests at 3 m	/	16	/	/	16
Total					
Number of padding samples impacted	3	25	8	4	40
Number of tests at 2 m	6	56	20	10	92
Number of tests at 3 m	2	56	20	10	88

Thus, this study aimed at experimentally testing the hypothesis according to which padding performance significantly changes with impact conditions and padding characteristics. For this purpose, padding was taken from ski areas to be representative of the padding used on slopes. This study extended the previous pilot study [6] (1) by testing additional padding and (2) by extending the investigation to trunk impact protection.

2. Methods

Experimental drop tests were performed on padding in ski areas, using an existing drop test device [6]. This device used an impactor, which was lifted above a piece of padding with a rope and dropped to induce impacts (Fig. 1).

2.1. Padding

The padding tested was obtained from two ski areas (altitudes: 1905 m and 2300 m). The padding was composed of foam enclosed in a PVC cover and made by various manufacturers. The only available information regarding the padding was: its dimensions, its manufacturer, conformity with the French standard, and age of the cover and the cover type (rough or smooth). On some padding samples, the initial PVC cover had been entirely replaced (called *new cover*), probably due to the cuts that had appeared on the original cover. For these padding samples, the cover age was different from the foam age. The characteristics of the tested padding are provided as [Additional material](#).

2.2. Impactors and instrumentation

The impactor was either a metallic headform (compliant with the NF EN 960 standard, size 625, 6 kg [8]) or a representative resin trunk (35 kg, length: 74 cm, width: 48 cm, thickness: 22 cm) in order to generate robust and reliable impacts similar to the normative ones but more representative of the impact conditions of CWOs [3]. The impactors were instrumented with tri-axial accelerometers (TE Connectivity, EGAS-S403A-250-/L1.5M, ± 250 g) located close to the center of mass. Linear accelerations were recorded at 10 kHz using a Slice Nano (DTS).

2.3. Drop tests

For each padding sample, 4 tests were performed: 2 from a height of 2 m (low-energy impacts) and 2 from a height of 3 m (high-energy impacts). Drop heights were chosen to approximate head and thoracic impact speeds (theoretical impact speed of 28 km/h for a 3-m fall) [3]. Only 2 samples of 10-cm thick padding were not impacted from 3 m to avoid damaging the sensors, as the tests from 2 m induced accelerations between 116 g and 291 g. Tests were performed during 3 test sessions in the winter (outside temperature: $[-1$ °C, 6 °C]) and during 1 session in the summer ([outside temperature: 8 °C; 28 °C]).

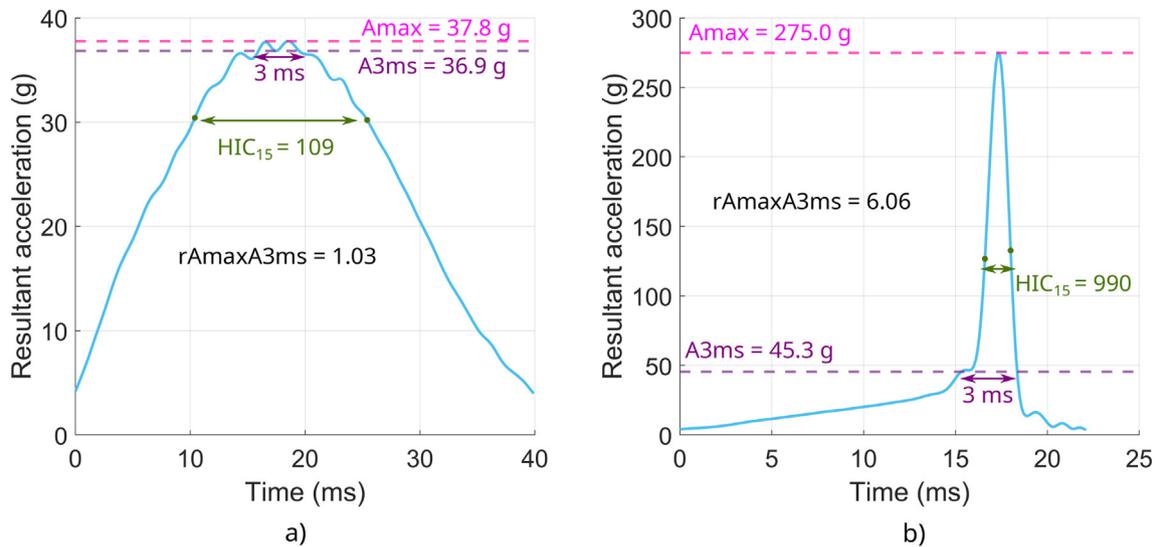


Fig. 2. Examples of curve shape: a) without bottoming-out (15-cm thick flat padding, head impact from 3 m) b) with bottoming-out (10-cm thick flat padding, head impact from 2 m).

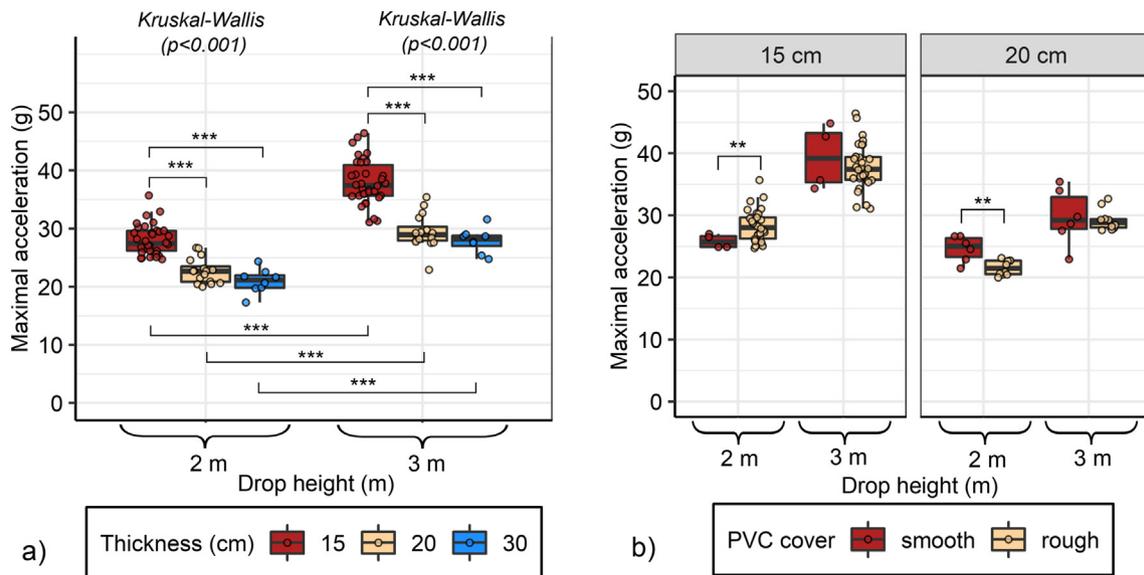


Fig. 3. a) Amax according to drop height (Wilcoxon or paired t-tests for each padding thickness: $P < 0.001$) and padding thickness (Kruskal–Wallis tests: $P < 0.001$ for each drop height) and b) Amax according to PVC cover type (Welch t-test or Wilcoxon test for each padding thickness, 2-m drop height: $P < 0.01$ and 3-m drop height: $P > 0.05$).

2.4. Studies

Three studies were conducted on the padding. The main study consisted in head impacts on flat padding freely laid on a wooden or concrete floor (Fig. 1a). The effects of the following parameters on impact accelerations were quantified: drop height, padding thickness (from 10 cm to 30 cm), temperature (as foam behavior can be temperature dependent), impact location (center or border), cover age (from 0 to 17 years old, measured from the year of manufacturing of the padding to the time of testing), type of PVC cover, cover replacement (initial cover or with a new cover).

In a complementary study, trunk impacts were performed on flat padding laid on the floor (Fig. 1b) to investigate the influence of the impactor (mass and shape). In another complementary study, head impacts were performed on padding with a specific shape (cylindrical or in 3 parts, Fig. 1c, d) placed on metallic poles with a diameter (6 cm, 9 cm or

16 cm) suited to the padding dimensions to investigate the combined influence of padding shape and padding position on the obstacle. Drop heights were limited to 2.9 m and 2.7 m for padding on poles (diameters of 16 cm and 9 cm) due to available ceiling height.

2.5. Post-processing

Data were post-processed with Matlab (2020) (MathWorks, Natick, Massachusetts, United States). Accelerations were filtered with a low-pass filter (Butterworth, cut-off frequency 600 Hz, 4th order) [6]. The analysis focused on the first impact between the impactor and the padding, excluding potential rebounds. The impact was defined as the time at which the resultant acceleration exceeded 4 g. Maximal accelerations (Amax) and 3 ms accelerations (A3ms, being the maximal acceleration exceeded during at least 3 ms) were computed from resultant accelerations. For each test, the ratio between Amax and A3ms

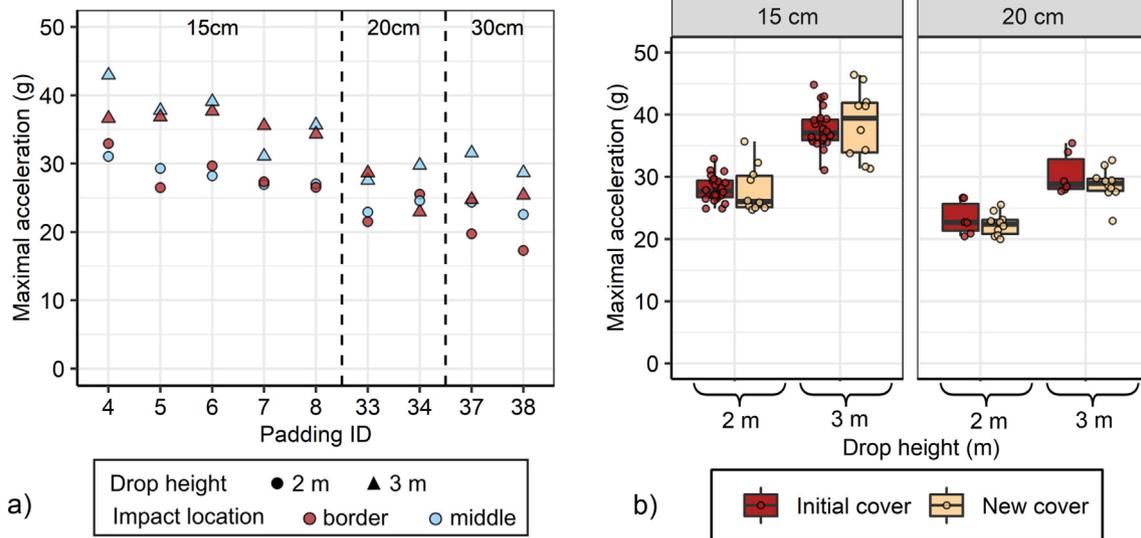


Fig. 4. Amax according to a) impact location (paired t-tests for each drop height: $P > 0.05$) and b) to cover replacement (Wilcoxon test or Welch t-test, $P > 0.05$ for all combinations of drop height and padding thickness).

(rAmaxA3ms) was computed to characterize the acceleration curve shape. Impact speeds were calculated by integrating vertical accelerations.

All statistical analyses were conducted on Amax values. A preliminary analysis underlined the influence of padding thickness and drop height ($P < 0.05$). Thus, the following analyses were performed separately for 2-m and 3-m falls and for different padding thicknesses (when observations were sufficient):

- The influence of padding thickness was quantified with a Kruskal–Wallis test followed by Dunn post-hoc tests (Bonferroni method)
- The effects of drop height, impact location and impactor were quantified with paired t-tests (or Wilcoxon test according to hypothesis-driven validation)
- The effects of PVC cover type and cover replacement were quantified with unpaired Welch t-tests or Wilcoxon tests
- The effects of temperature and cover age were quantified with Pearson and Kendall correlations.

Trunk accelerations were compared with head accelerations recorded on the same padding. Head accelerations on 15-cm thick padding on obstacle were compared with head accelerations on 15-cm thick padding on the floor, summarized as an experimental corridor. This corridor included all the acceleration curves for a given padding thickness and drop height. Statistical analyses were performed with R (R Core Team (2015), Vienna, Austria) and the influence of a parameter was deemed significant for P -value lower than 0.05.

3. Results

180 impacts were performed on 40 padding including 124 head impacts on padding on the floor, 24 trunk impacts on padding on the floor and 32 head impacts on padding on obstacles (Table 1). Falls from 2 m (respectively 3 m) induced impact speed at 20.5 ± 1.1 km/h (respectively 24.9 ± 1.0 km/h). Associated impact energies were 82 ± 34 J (respectively 127 ± 43 J) for head impacts from 2 m (respectively 3 m), and 643 ± 45 J (respectively 911 ± 58 J) for trunk impacts from 2 m (respectively 3 m).

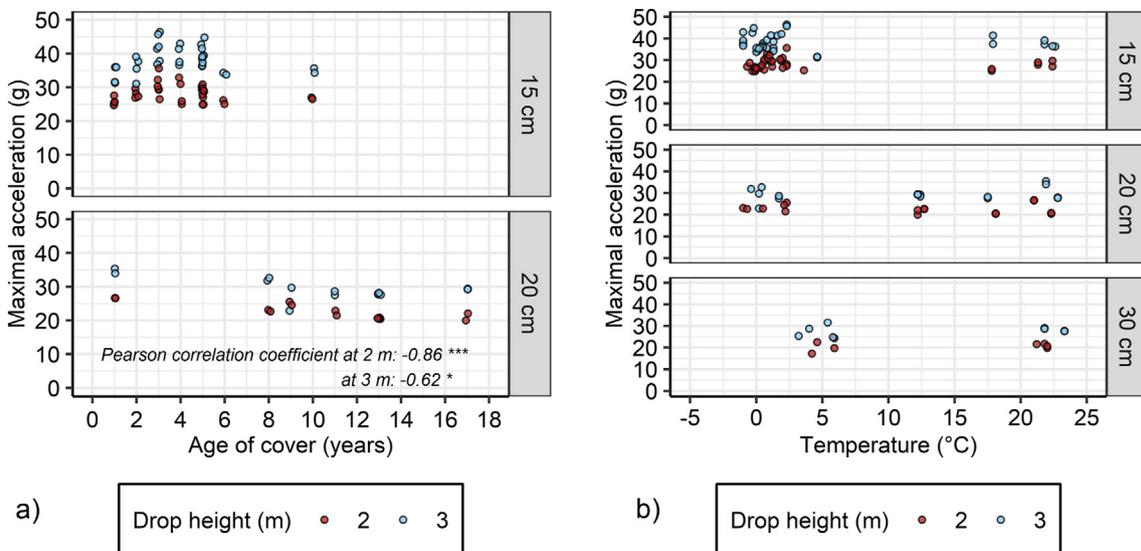


Fig. 5. Amax according to a) age of the cover (Kendall correlations: $P > 0.05$ for 15-cm thick padding and Pearson correlations: $P < 0.05$ for 20-cm thick padding) and to b) outside temperature (Kendall correlations, $P > 0.05$ for all combinations of drop height and padding thickness).

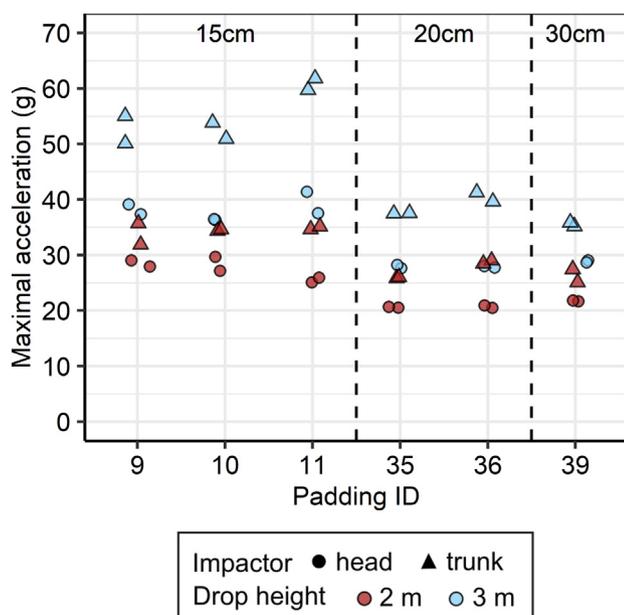


Fig. 6. Amax according to impactor and drop height.

3.1. Head impacts on padding on the floor

All head impacts on 15-cm, 20-cm or 30-cm thick padding on the floor were characterized by low accelerations ([17 g; 47 g]) and bell-shaped acceleration curves (i.e. without bottoming-out, Fig. 2a) underlined by rAmaxA3ms values close to 1 (1.012 ± 0.007). For 10-cm thick padding, the acceleration curves presented higher Amax ([91 g; 291 g]) and rAmaxA3ms values ([1.34; 6.54]), indicating foam bottoming-out (Fig. 2b). 10-cm thick padding samples were excluded from the rest of the analyses as their performance was too low compared to thicker padding samples and unable to offer sufficient protection.

Drop height increased the Amax ($P < 0.001$, Fig. 3a) and padding thickness decreased the Amax ($P < 0.001$, Fig. 3a). The Amax on 15-cm thick padding (2 m: 28.1 ± 2.6 g, 3 m: 38.0 ± 3.9 g) were higher than the Amax on 20-cm thick padding (2 m: 22.7 ± 2.2 g, 3 m: 29.4 ± 2.9 g) and on 30-cm thick padding (2 m: 21.0 ± 2.1 g, 3 m: 27.9 ± 2.1 g). Concerning the effect of the PCV cover type for 2-m falls, smooth covers decreased the Amax for 15-cm thick padding but increased the Amax for 20-cm padding compared to rough covers ($P < 0.01$, Fig. 3b). The PVC cover type did not affect the Amax for 3-m falls ($P > 0.05$), nor did the impact location for all drop heights ($P > 0.05$, Fig. 4a). The preliminary analysis did not show a significant effect of cover replacement (initial cover versus new cover, Fig. 4b). A negative correlation was observed between the Amax and the cover age for 20-cm thick padding, but no correlation was found for 15-cm thick padding ($P < 0.05$, Fig. 5a). The Amax was not correlated with outside temperature ($P > 0.05$, Fig. 5b).

3.2. Trunk impacts

Trunk impacts were also characterized by curve shapes without bottoming-out and rAmaxA3ms values close to 1 (1.02 ± 0.01). Considering all padding thicknesses, trunk impacts induced higher Amax values (on average +6.5 g and +13.4 g respectively for 2-m and 3-m falls) compared to head impacts (Fig. 6, $P < 0.001$).

3.3. Head impact on padding on obstacle

Cylindrical padding placed on obstacles was characterized by variable accelerations ([13.4 g; 218.2 g]), rAmaxA3ms ([1.00; 5.76]) values and curve shapes (Fig. 7a). Impacts on cylindrical padding on obstacles either induced lower (Fig. 7b, e), equivalent (Fig. 7c, f, padding: 25, 26) or higher (Fig. 7c, f, g, padding: 22, 27, 28) accelerations than impacts on

flat padding on the floor. Drop height also modified acceleration values and curve shapes.

4. Discussion

This study was the first to investigate the influence of various factors on the ability of padding to dissipate energy during an impact. It builds on the previous pilot study [6] by including a large number of padding samples (40) and factors (9). The use of isolated head and trunk impactors was preferred as these tests were close to the normative evaluation, though more representative, and numerous tests could be carried out in ski areas. Rigid head and trunk impactors were chosen to characterize the padding behavior only and to provide experimental data for future numerical padding models.

This study investigated padding performance in impact conditions representative of their use on slopes, as head and trunk impact characteristics were identified as the main focus for padding performance evaluation [3]. Though the experimental impact speeds were slightly lower than the theoretical ones (20.5 ± 1.1 km/h versus 22.6 km/h for 2-m falls and 24.9 ± 1.0 km/h versus 27.6 km/h for 3-m falls) due to rope friction during the fall, they were still consistent with mean head and trunk impact speeds [3]. The tests were also performed under representative environment conditions (temperature and atmospheric pressure of ski slopes) to consider their potential influence on the foam's behavior and on the air trapped inside the padding. As our objective was to evaluate representative padding as found *in situ* and not to perform normative impacts or laboratory tests, the padding samples tested were obtained from the slopes.

This study confirmed the strong influence of padding thickness and drop height (i.e. impact speed) on padding performance, as previously observed [4–6]. These results were expected but they highlighted the insufficient ability of the 10-cm thick padding samples to limit head accelerations. The mass and shape of the impactor also had a strong influence on impact accelerations. The trunk was 5.8 times heavier than the head but its impact surface was also approximately 2.1 times bigger. Heavier impactors penetrate deeper into the padding but larger impactors penetrate less as the mass is better distributed. For the tested conditions, the heavier mass of the trunk was not compensated by the larger impact surface, causing higher accelerations. Contrary to the pilot study [6], the tested outside temperatures did not significantly influence impact accelerations. Though impacts were performed in larger temperature ranges in the current study, the impacts were not performed on the same padding at different temperatures as in the pilot study. The temperature influence may be of the same order of magnitude than the variability observed between padding samples. Moreover, the temperature was measured on the padding surface and may be different from the temperature on the foam surface and in the foam core. The air trapped inside the welded cover may act as thermal insulation, limiting temperature variation inside the foam.

Different trends on the influence of the cover type were observed with no significant influence at high energy but significant and opposite influence at low energy depending on padding thickness. We can hypothesize that the cover type has a relatively minor influence on padding performance and that the differences observed were mostly driven by other padding characteristics. Similarly, the cover replacement (*new cover*) did not significantly influence padding performance. The major advantage of the *new cover* is to allow padding repair (for example after a cut caused by the edge of a ski) instead of a full replacement. Cover cuts may be associated with foam cuts and may have allowed water to get inside the foam, freeze and cause structural damage or change local absorption properties. Future studies should target cover replacement to investigate the consequences of this process on padding performance before expressing recommendations for ski areas. The foam of newly covered padding may also be older, though this parameter could not be investigated as the padding age was written on the cover and therefore lost when the cover was replaced.

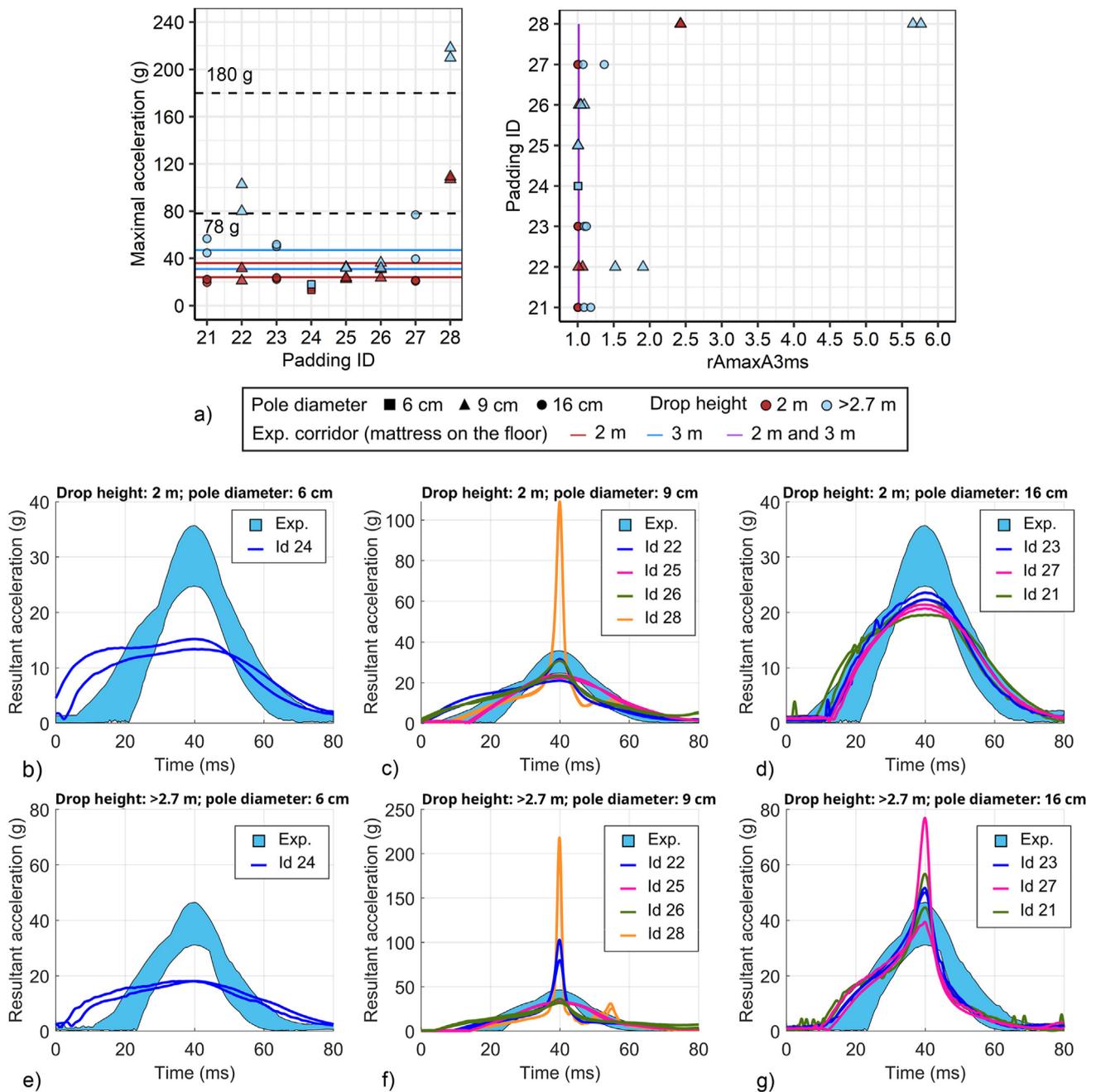


Fig. 7. a) Comparison of Amax and rAmaxA3ms values between padding on the floor or on poles; b) to g) comparison of acceleration curves of padding on obstacle with experimental corridors based on tests on the floor.

Large variations of Amax were observed when cylindrical padding was placed on an obstacle. These variations may be caused by the specific shape of cylindrical padding that may change the foam behavior, the influence of the air and of the cover. The cylindrical shape may also favor local loading of the foam or amplify the penetration of the head on the padding. Additional tests are required to better understand all these phenomena.

Amax values induced by head impacts from 3 m on 15-cm thick padding (38 ± 4 g) were much lower than equivalent impacts on hard snow (138 ± 6 g [9]) or impacts of a Hybrid-III head on a steel anvil (1043 g [10]). We hypothesized that for head impacts on padding, the metallic headform and the Hybrid III head would give similar

acceleration responses due to their similar dimensions. Due to the higher rigidity of the impactors (headform, Hybrid III), most of the deformations would be sustained by the padding. Moreover, the headform gave conservative results due to its heavier mass (and therefore, higher impact energy) compared to the Hybrid III head. For some head impacts on padding, the accelerations reached the 78-g threshold used to assess the risk of concussion based on accident reconstructions using Hybrid III dummies [11]. These tests were also associated with rAmaxA3ms values above 1.2, indicating a beginning of bottoming-out (Fig. 8). For these tests, the padding reached its absorption limit and an additional impact energy would induce an important acceleration increase. Some head impacts even reached the 180-g threshold used to evaluate the risk of

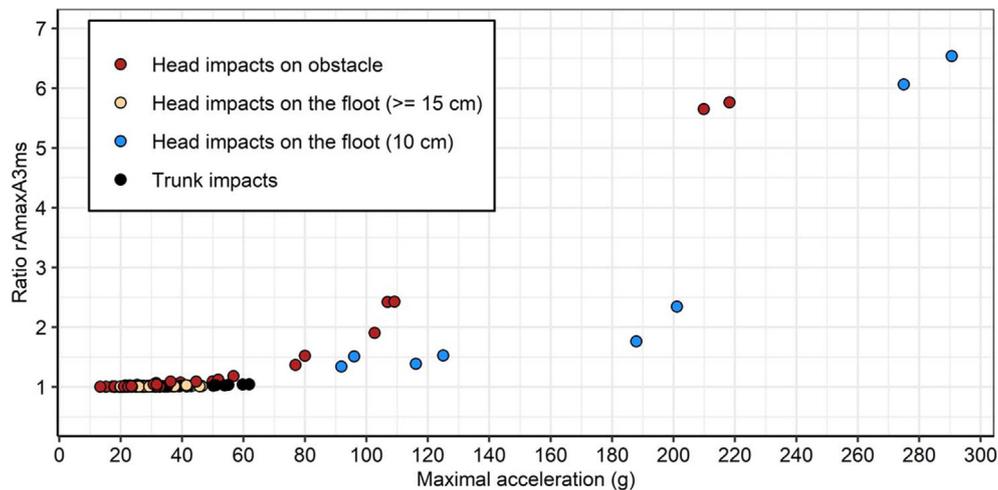


Fig. 8. Evolution of rAmaxA3ms ratio according to maximal accelerations.

severe injuries [12]. Accelerations above thresholds occurred for impacts on 10-cm thick padding and on cylindrical padding on obstacles (Fig. 8).

5. Limitations

Padding samples were retrieved from padding used on ski slopes. Therefore, padding characteristics could not be controlled, sometimes resulting in small groups for the statistical analysis. The influence of some factors (such as PVC cover type, outside temperature, cover age or *new cover*) could not be investigated on the same padding samples. Furthermore, information such as the type of cell foam, the material or the density was not available. The padding was stored indoors during the summer and the padding usage during the winter is not documented. Thus, the age of the padding did not necessarily coincide with the number of seasons used, nor with the age of the cover (in case of *newly covered* padding). To prevent damage to the padding, impact speeds above 25 km/h were not investigated. Moreover, testing constraints prevented us from performing tests on obstacles at a drop height above 2.9 m.

6. Conclusions

This study provides an evaluation of the key parameters influencing ski padding performance to protect from an injury during a collision. This evaluation was made under 4 representative impact conditions: a small and penetrating impactor (head) and a large impactor (trunk) at 20 km/h and 25 km/h. This study provides novel data for use in developing new performance tests for padding used in winter sports. Working groups are currently discussing the evolutions of the padding standard and the best practices related to padding. These evolutions include a more representative evaluation of padding performance and recommendations for better resort safety management.

Future studies, for example based on numerical simulations or experimental tests with a dummy, should extend this work to higher-impact energies to more precisely determine the limits of padding performance to protect from mild and severe injuries but also to confirm the influences observed, as higher energies might reveal new influential parameters. Complementary analyses are also needed to better understand the way in which wider temperature ranges affect foams and padding, and to evaluate the local consequences of padding repairs. Experimental tests performed on new padding might help to characterize the influence of specific parameters.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsampl.2023.100038>.

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