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1 About some factors influencing safety mattress performances in head impact collisions: a  
2 pilot study

3

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6

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16

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21

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1 **Abstract:**

2 **Objectives:** In recreational snow sports activities, safety mattresses are placed on obstacles  
3 to prevent injuries from a collision with users. However, the performances of these devices  
4 in field conditions remain unclear. The objective of this study is to evaluate the effect of  
5 mattress thickness, impact speed, impacting mass and atmospheric conditions on head  
6 acceleration during an in-field impact on safety mattress. **Design and Methods:** 42 in-field  
7 experimental drop tests of a normative metallic head were conducted on safety mattress to  
8 assess the influence of impact speed (5.8m/s or 7.3m/s), impacting mass (6kg or 11.6kg),  
9 outside conditions (3 conditions) and mattress thickness (24cm, 32cm, 44cm) on head  
10 acceleration at impact. Linear accelerations were measured and Head Injury Criteria 15ms  
11 (HIC<sub>15</sub>) was computed. A statistical analysis (ANOVA) was used to characterize the effects  
12 of the varying parameters on maximal acceleration and HIC<sub>15</sub>. **Results:** Reduced impact  
13 speed, increased mattress thickness and change in the outside conditions significantly  
14 decreased the head acceleration and HIC<sub>15</sub> ( $p < 0.001$ ). The effect of the impacting mass on  
15 head acceleration was not significant. **Conclusions:** This study highlights the influence of  
16 impact speed, atmospheric condition and mattress construction on absorption capacities of  
17 safety mattresses. It is a first step toward a better understanding and evaluation of safety  
18 mattresses performances.

19

20 **Keywords:** Safety, Snow sports, Head, Protection, Mattress

21

22 **Introduction:**

23 Artificial and natural obstacles (such as trees, pylons, ski lift poles, and snow guns) are often  
24 located close to ski slopes. Collisions occurring against these obstacles are relatively rare  
25 among ski patrols rescues (1% in France<sup>1</sup> and respectively 5.6% and 3.6% for skiers and  
26 snowboarders in the USA<sup>2</sup>). Nevertheless, the consequences of these accidents can be  
27 serious as collisions against obstacles (CO) accounted for 82.4% of fatalities on ski slopes in  
28 US between 1976 and 1992<sup>3</sup> and respectively 35.1% and 21% of the traumatic deaths on ski

29 slopes in Austria between 2005 and 2010<sup>4</sup> and in France between 2010 and 2018<sup>5</sup>. Recent  
30 work on traumatic brain injury (TBI) in skiing has also shown that CO are an important cause  
31 for the most severe TBI<sup>6</sup>. All of these studies highlight the importance of (i) better  
32 understanding CO, (ii) promoting public awareness campaigns, (iii) working on accidents'  
33 prevention and (iv) improving existing safety devices' capabilities to properly dissipate  
34 impact energies.

35

36 Safety mattresses are designed to reduce injury likelihood and severity for skiers and  
37 snowboarders during a collision against artificial and natural obstacles. In some countries,  
38 the design and performance at impact of these mattresses are regulated by standards (for  
39 example, NF S52-105 in France<sup>7</sup>). However, the outside temperature and the atmospheric  
40 pressure during these impact tests were not investigated nor included in normative  
41 requirements<sup>7</sup>. These normative tests are conducted in laboratory conditions, which may  
42 significantly differ from on-field conditions. Hence, many parameters, either intrinsic (such as  
43 thickness or material) or extrinsic (such as fixation device or atmospheric conditions:  
44 pressure, temperature, humidity) to the mattress, could influence its performances.

45

46 To our knowledge, accelerations during impacts on ski mattresses were analyzed by three  
47 studies. Petrone et al.<sup>8,9</sup> performed tests on different protection devices used in international  
48 ski competition including A-nets, B-nets, air mattresses and foam mattresses. They found  
49 that both the protection device, the layout and the impact speed had an influence on the  
50 body acceleration. However, the foam mattresses studied were very specific to ski  
51 competition and quite different from the conventional foam mattresses used on recreational  
52 ski slopes. Recently, Scher et al.<sup>10</sup> investigated head and neck injury risks during impacts  
53 against different recreational ski slopes mattresses using an anthropomorphic dummy. They  
54 found a limited effect of the mattress in reducing the risk of severe brain and neck injuries.

55 However, to our knowledge, the effect of the impacting speed, mass and atmospheric  
56 conditions have never been investigated for these mattresses.

57

58 The objective of this work is: (1) to describe a portable experimental design to perform in-  
59 field evaluation of safety mattress performance and (2) to evaluate the effect of mattress  
60 thickness, impact speed, impacting mass and atmospheric conditions on head acceleration  
61 during an in-field impact on safety mattresses.

62

### 63 **Material and methods:**

64 The experimental set up was a portable drop test device initially developed to characterize  
65 the snow behavior in impact conditions<sup>11</sup>. The testing device produced a fall of a metallic  
66 instrumented head (which complies with EN 960 standard, size 625) on a safety mattress  
67 (Figure 1a). The lift and fall of the head were realized with a rope-pulley system and impacts  
68 occurred on the top of the head. The head acceleration was recorded with tri-axial  
69 accelerometers (EGAS-S403A-250-/L1.5M, measuring range:  $\pm 250g$ ; resolution: 1g)  
70 mounted at the center of mass of the head. Accelerations data were recorded with a KiDAU  
71 system (Kistler) with a sampling frequency of 10,000Hz. Impacts were filmed with a high-  
72 velocity camera (Photron SA3, 1024x1024pixels, 1000images/second, 18-200mm) and  
73 impact speeds were measured by digital image correlation on GOM software (GOM GmbH,  
74 Braunschweig, Germany).

75

76 Four parameters were evaluated: impact speed, impacting mass, mattress thickness and

77 atmospheric conditions. Impacts were performed from two heights: 2m and 3m,

78 corresponding to theoretical impact speeds of 6.3m/s and 7.7m/s, respectively. These

79 impact speeds were chosen based on numerical reconstructions of collisions against

80 obstacle while skiing (mean normal head impact speed of 28km/h or 7.8m/s)<sup>12</sup>. The

81 impacting mass was either 6kg, the mass of the metallic headform, or 11.6kg consisting in

82 the headform plus a 9cm thick metallic plate fixed at its bottom (Figure 1b). Tests were  
83 performed on three safety mattresses (2mx1m, same open cell foam and PVC cover) of  
84 different thickness (24cm, 32cm and 44cm). Mattresses were left outside the previous night  
85 to reproduce realistic conditions. Three atmospheric conditions were evaluated on two  
86 different winter days:

87 - Condition A: altitude of 2,375m with a temperature between 5.7°C and 6.7°C and a wind  
88 speed of 2km/h (under shelter measures obtained from Météo France at an altitude of  
89 1,950m).

90 - Condition B: altitude of 1,612m with a temperature between -6°C and -3°C.

91 - Condition C: altitude of 1,612m with a temperature between 5°C and 6°C.

92 For conditions B and C, mattresses were impacted on tarmac. For condition A, the ground  
93 was recovered by icy snow (hand hardness 5). To prevent the snow from deforming under  
94 the mattresses and ensure a rigid ground, a Plexiglas plate was placed below mattress, at  
95 the impact point. The mattress' motion was also restricted laterally with poles planted in the  
96 snow (Figure 1a). Each impact condition was repeated once at the same impact location for  
97 a total of 42 drop test. A minimum of 2 minutes was observed between each test (Figure 1c).

98

99 The post-processing analysis of the acceleration signals was performed using Matlab 2013a  
100 (MathWorks, Natick, Massachusetts, USA). Firstly, accelerations were individually filtered  
101 with a low-pass filter (Butterworth order 4, cut-off frequency of 600Hz). The acceleration  
102 signals were then restricted to a window of  $\pm 100\text{ms}$  around the first impact peak of the head  
103 on the mattress.

104

105 The output parameters, extracted from the resultant acceleration on the first peak, were: the  
106 maximal acceleration  $a_{\text{max}}$  and the Head Injury Criteria score for a duration of 15ms ( $\text{HIC}_{15}$ ).

107 The  $\text{HIC}_{15}$  is computed as follows<sup>13</sup>:

108

$$\text{HIC}_{15} = \max\left((t_2 - t_1) \cdot \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \cdot dt \right]^{2.5}\right)$$

109 *with  $t$  being the time in seconds,  $(t_2-t_1)$  being equaled to 0.015s and  $a(t)$  being the resultant*  
110 *linear acceleration in g.  $HIC_{15}$  and  $a_{max}$  are two injury criteria for the head based on the*  
111 *resultant linear acceleration with threshold values of 700 for  $HIC_{15}$ <sup>13</sup> and around 80g for*  
112  *$a_{max}$ <sup>14,15</sup>. A factorial ANOVA was used to evaluate the effect of height drop, impacting mass,*  
113 *mattress thickness and weather conditions (R Studio 1.2.5033, Boston, Massachusetts,*  
114 *USA) on  $a_{max}$  and  $HIC_{15}$ .*

115

## 116 **Results:**

117 Typical kinematics of the head are shown on Figure 1d. The impact speeds measured on  
118 videos were  $5.8\pm 0.2$ m/s for the 2m fall and  $7.3\pm 0.1$ m/s for the 3m fall. The impact energies  
119 were estimated at 102J for '2m-6kg', 159J for '3m-6kg', 197J for '2m-11.6kg' and 308J for  
120 '3m-11.6kg'. The resulting accelerations showed a bell shape for the first impact peak with  
121 impact durations ranging from 50.2ms to 123.4ms (Figure 2). Values of  $a_{max}$  ranged from  
122 14.6g to 32.2g whereas  $HIC_{15}$  varied between 11 and 75. The absolute variations between  
123 repetitions of  $a_{max}$  and  $HIC_{15}$  were respectively below 3.2g and 15 for the 24cm thick  
124 mattress and below 2.2g and 5 for the 44cm thick mattress (Figure 3). These variations were  
125 slightly larger for the 32cm thick mattress (up to 6.1g and 26).

126

127 Drop height significantly increased the head acceleration at impact for similar impact  
128 duration ( $p<0.001$  for  $a_{max}$  and  $HIC_{15}$ ) (Figure 2a and Figure 3): increasing the drop height  
129 from 2m to 3m increased  $a_{max}$  up to 12.5g and  $HIC_{15}$  up to 46. Increased mattress thickness  
130 was associated with lower  $a_{max}$  ( $p<0.001$ ) and  $HIC_{15}$  ( $p<0.001$ ) values (Figure 3) and longer  
131 impact durations (see curves on Figure 2b). These variations were larger at higher energies  
132 (mass 11.6kg and drop height of 3m) than at smaller energies (mass 6kg and drop height of  
133 2m) (Figure 2b and Figure 3). There was a significant effect of the atmospheric conditions on  
134 the recorded accelerations ( $p<0.001$  for  $a_{max}$  and  $HIC_{15}$ ): increased temperature (condition C  
135 vs condition B) was associated with reduced  $a_{max}$  and  $HIC_{15}$  values (Figure 2c and Figure 3).

136 However, the impacting mass did not significantly affect  $a_{\max}$  nor HIC<sub>15</sub> values, though small  
137 variations of the accelerations did occur with the increase of the impacting mass (Figure 2d  
138 and Figure 3).

139

#### 140 **Discussion:**

141 The first objective of this work was to develop an experimental method to assess safety  
142 mattress performances using headform impacts in-field testing conditions. The primary  
143 advantage of the test device was its portability and its ability to characterize safety  
144 mattresses performance using in-field, on-slope test conditions (high altitude, low  
145 temperature...). These tests showed that increasing the drop height, and so the impact  
146 speed, induced a significant increase of acceleration, and so did the decrease of mattress  
147 thickness or the variation of outside conditions. Increasing the impacting mass did not  
148 induce significant acceleration's variations.

149

150 In regard to the tested conditions, the head acceleration was not significantly affected by the  
151 impacting mass whereas the impact speed had a significant influence. Both impact speed  
152 and impacting mass increased the impact energy: by a ratio of 1.6 for the impact speed and  
153 by 1.9 for the mass in this experiment. Increasing the impacting speed induced higher  
154 impact energy but also higher strain rates in the foam, whereas increasing the impacting  
155 mass only increased the impact energy. This suggest that the impact energy was not the key  
156 factor, but rather that the strain rate of the mattress defined the acceleration of the impacting  
157 headform. This might be explained by the mechanical behavior of the foam in the mattress:  
158 First, polymeric foams are known to be strain rate dependent, with higher compression  
159 stress or load with increasing compression speed for polyurethane foams<sup>16,17</sup>. This is  
160 consistent with the higher head accelerations seen with increased impact speeds. Second,  
161 polymeric foams usually exhibit a three stages mechanical behavior: linear elasticity,  
162 collapse and densification<sup>16</sup>. Foam are very effective at absorbing the energy during the  
163 collapse phase in which the transmitted force and thus the head acceleration is



164 approximately constant. In our experiment, even though increasing the mass almost doubled  
165 the impact energy, it seems that the mattress foam did not reach the densification and thus  
166 the head acceleration remain the same. The strong influence of impact speed on impact  
167 accelerations was also qualitatively seen by Petrone on ski competition safety mattress with  
168 thicker mattress and higher impact velocities<sup>8</sup>. In future works, dedicated experiments will be  
169 performed to investigate strain rate dependency under compression tests, in order to better  
170 assess ski safety mattress foams mechanical behavior. A sensitivity analysis (with numerical  
171 simulations and experimental tests) on the effect of the impacting mass will also be  
172 performed in future works. Particularly, it would be useful to determine the impact energy  
173 required to reach mattress' densification (also called bottoming out). Such information could  
174 be very useful to assess safety performance of such device. Indeed, the impact speeds were  
175 chosen based on a previous study to represent a mean behavior on slopes<sup>12</sup> but CO may  
176 occurred after too high speeds on slopes<sup>6</sup>.

177

178 Variation of the outside conditions (altitude and temperature) led to significant variations of  
179 head acceleration. In particular, colder temperatures induced higher head accelerations  
180 during the impact. These results are consistent with the important influence of temperature  
181 on polymeric foams, for which a decrease of the foam temperature induced higher impact  
182 force and lower foam deformation<sup>18</sup>. Given the significant influence of outside conditions on  
183 ski mattress, we recommend, for future studies, investigating the effect of different  
184 atmospheric parameters (humidity, temperature, atmospheric pressure) on mattress  
185 performance, in a controlled environment. A way of improving safety mattress is related to  
186 consider realistic temperature ranges as those observed on ski resorts for the foam  
187 calibration, which is currently not addressed by existing regulation procedures.

188

189 Finally, with increasing mattress thickness, the energy absorption along time is more  
190 progressive with lower maximum accelerations and longer impact durations; this should  
191 provide increased safety. The influence of the impact energy on the thickness highlights the

192 need of precisely quantifying the impact energies that safety mattresses **should** absorb  
193 without inducing **injurious** accelerations. For that, an epidemiological analysis is firstly  
194 recommended to characterize the conditions of **CO**. This analysis should be followed by  
195 numerical simulations with human model under impact conditions against mattress to get a  
196 relevant estimation of impact speeds, impact energies and contact surfaces with the  
197 mattress. These two steps are compulsory to a better comprehension of these accidents and  
198 then to a better protection of the users.

199

200 Epidemiological study showed that severe TBI can be caused by **CO**<sup>6</sup>. In this study, **HIC<sub>15</sub>**  
201 and maximal accelerations were used to identify the risk of head injury. All impact conditions  
202 led to **a<sub>max</sub>** and **HIC<sub>15</sub>** values below the injury thresholds. Three hypotheses can explain the  
203 non-injurious impacts of this study. First, the epidemiological study did not mention if the  
204 obstacle was protected<sup>6</sup> and Scher et al. showed that adding a mattress on a wooden pole  
205 significantly decreases the maximal head acceleration and **HIC<sub>15</sub>** values<sup>10</sup>. Second,  
206 rotational accelerations computation are additional metrics to assess head injury  
207 occurrence<sup>15</sup>. In this work, only linear accelerations were considered. This choice was  
208 supported by head kinematics analysis (without any rotation) during the drop test impact. In  
209 different testing conditions (with rotational velocities), Scher et al. showed that mattresses  
210 reduced linear accelerations but had no significant effect on rotational accelerations<sup>10</sup>.  
211 Finally, the impact energies in our study may be lower than the energies of **CO** leading to  
212 severe TBI and for which foam densification may occur.

213

214 Two major impact tests are conducted in the French standard<sup>7</sup> with either the fall of a 30kg  
215 hemispheric mass or of a 30kg flat mass for respective impact energies of 100J and 440J.  
216 Our tests were not conducted in the standard's conditions but focused on reproducing  
217 realistic head impact through its mass and impact speed. Our current experiments were  
218 closer to the first testing conditions of the standard, given the head geometry and impact

219 energies. However, if the impact energies were similar, the impact speeds significantly differ  
220 (theoretically around 2.6m/s in the standard test for same testing conditions versus from  
221 5.8m/s to 7.3m/s in the current study). The effects of impact speed, impact energy and  
222 impacting mass were previously discussed as well as the likely effect of strain rate. Thus,  
223 evaluating safety mattress with representative speeds seems to be a key point for further  
224 evolutions of regulated procedures. In addition to that, analyzing the influence of the shape  
225 of the impacting structure seems of major importance, as started in the standard (a large  
226 impacting surface versus a small one might lead to a smaller penetration). The choice  
227 performed in this study was to be relevant with the reality of head impact condition<sup>6</sup>. Further  
228 studies will be devoted investigating the effect of the impacting mass' shape (for example a  
229 representative surface for the thoracic impact).

230

231 Nevertheless, this study has some limitations. First, all the atmospheric parameters were not  
232 be measured on the test's site and if some parameters were obtained from meteorological  
233 sources in the resort, other remained unknown (air humidity, atmospheric pressure...).

234 Mattresses were also tested flat on a surface assumed to be rigid (icy snow with Plexiglas  
235 plate or tarmac) to improve the repeatability of the tests. This position is close to a mattress  
236 mounted on large pylons or snow barriers, but the experimental design needs to be adapted  
237 to represent impacts on mattresses mounted on snow guns or small posts. Furthermore, the  
238 influence of the ground properties on the mattress performance were limited in condition A  
239 with tests on icy snow combined with the Plexiglas plate and in conditions B and C with a  
240 hard ground. Considering the similar performance between two tests repetition, the influence  
241 of the ground was considered to be small. The time between two consecutive tests was not  
242 evaluated, but again the similar performance between two repetitions is in favor of a  
243 sufficient time for the foam to recover for most of the tests. Moreover, mattresses were  
244 tested twice in each condition. Additional repetitions should be realized to properly conclude  
245 on the repeatability of the tests, without leading to a conditioning of the foam. Finally, we  
246 chose to investigate safety mattresses performances in head impact conditions using a

247 metallic head complying with helmet standards. [If this head is more rigid than a human head,](#)  
248 [this allowed testing the mattresses with a realistic mass and geometry and the head rigidity](#)  
249 [limited tests variations.](#)

250

## 251 **Conclusion**

252 This work provided a first analysis of the variability of the performances of [recreational ski](#)  
253 [slopes safety mattresses in-field testing head impact conditions.](#) The experimental device  
254 showed the capacities to characterize safety mattresses performances. Furthermore,  
255 mattresses performances are [significantly affected by their thickness but also by impact](#)  
256 [speeds and outside conditions \(p<0.001\)](#) and the impact energy alone is not sufficient to  
257 characterize an impact. The tests conducted also highlighted the [importance for](#) evaluating  
258 mattresses in realistic conditions [of speed, energy and outside conditions.](#) They also draw  
259 attention on the need of a better comprehension of the [behavior of mattress' foam, for](#)  
260 [example through stress-strain curves, and on the parameters affecting this behavior \(strain](#)  
261 [rates, air humidity, foam temperature, aging of the mattress...\).](#)

262

## 263 **Practical implications**

- 264 • The experimental set-up has shown the capacities to assess safety mattresses  
265 performances in field testing conditions through drop tests in different testing  
266 conditions.
- 267 • The impact speed, [the outside conditions](#) and the mattress thickness have shown to  
268 have a strong influence on mattress absorption capacities.
- 269 • This study offers a first basis towards a better [understanding](#) of ski safety mattress  
270 absorption capacities and [a first step](#) towards a better protection of collisions against  
271 obstacle in recreational snow sports.

272

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320 **Figures legend**

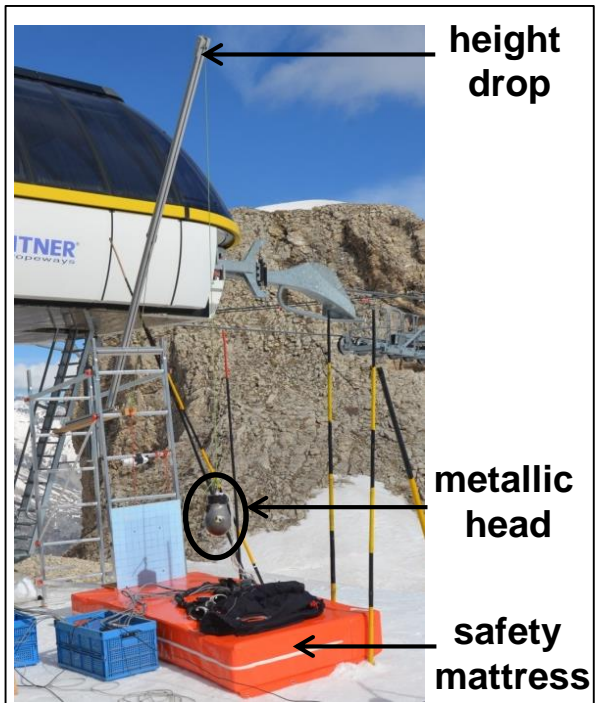
321 Figure 1: experiments description - a) experimental drop test set up, b) head with and  
322 without the additional mass, c) design of experiment conducted twice on each mattress,  
323 and d) head kinematic during a test (24cm thick mattress, 3m 6kg)

324

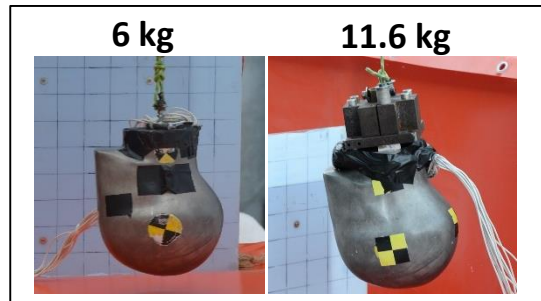
325 Figure 2: a) effect of drop height, b) of mattress' thickness, c) outside conditions and d)  
326 impacting mass on the mean resultant acceleration (the mean was computed over the two  
327 repetitions of the tests)

328

329 Figure 3: a)  $a_{max}$  and b)  $HIC_{15}$  values for each combination of drop height, impacting mass,  
330 mattress' thickness and outside conditions tested



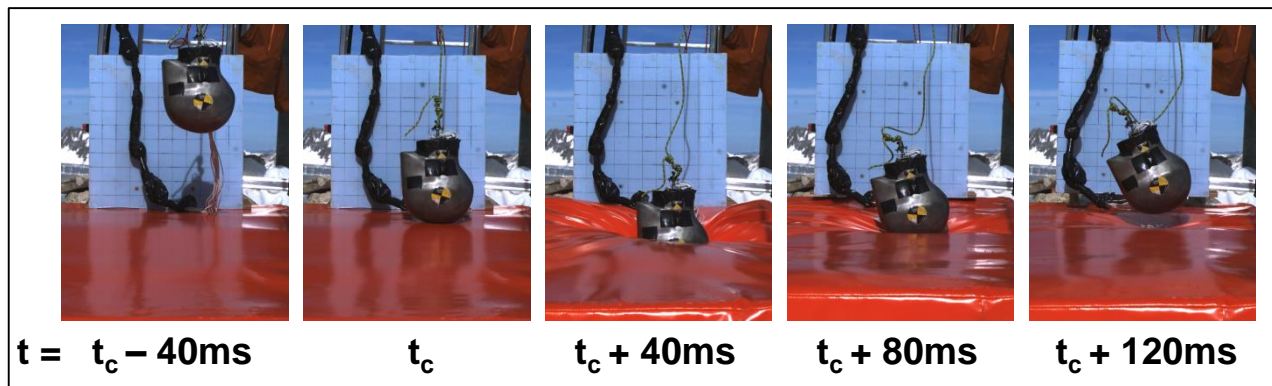
a)



b)

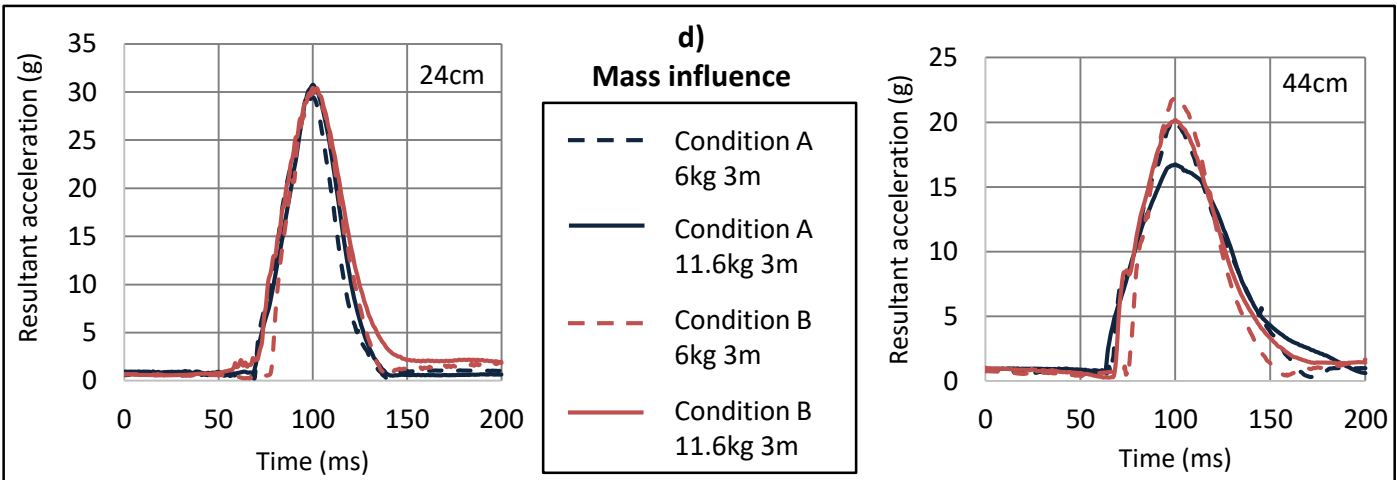
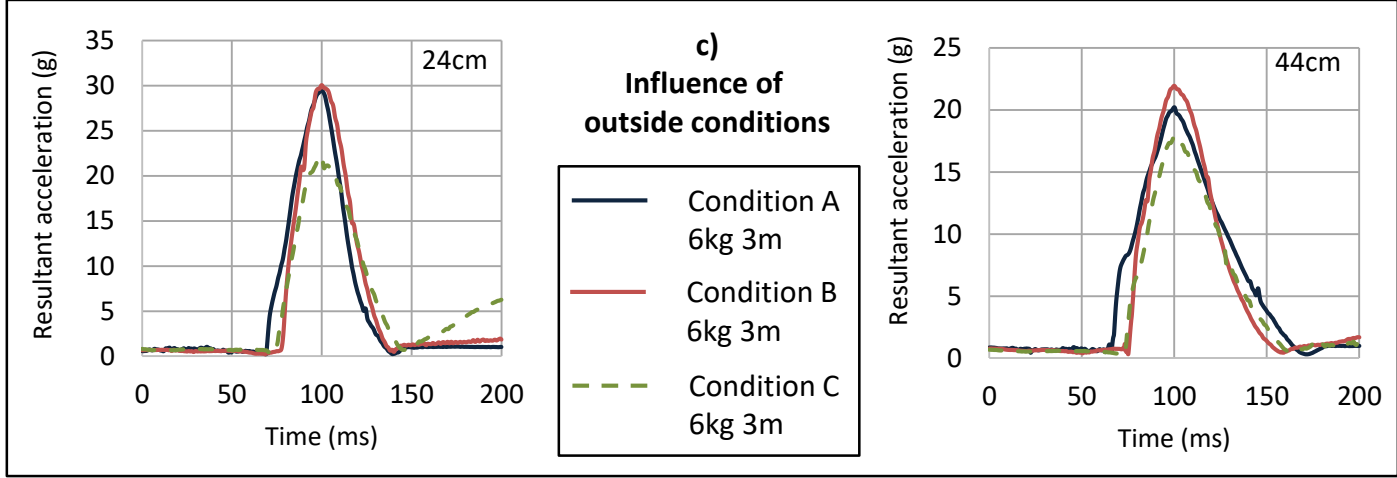
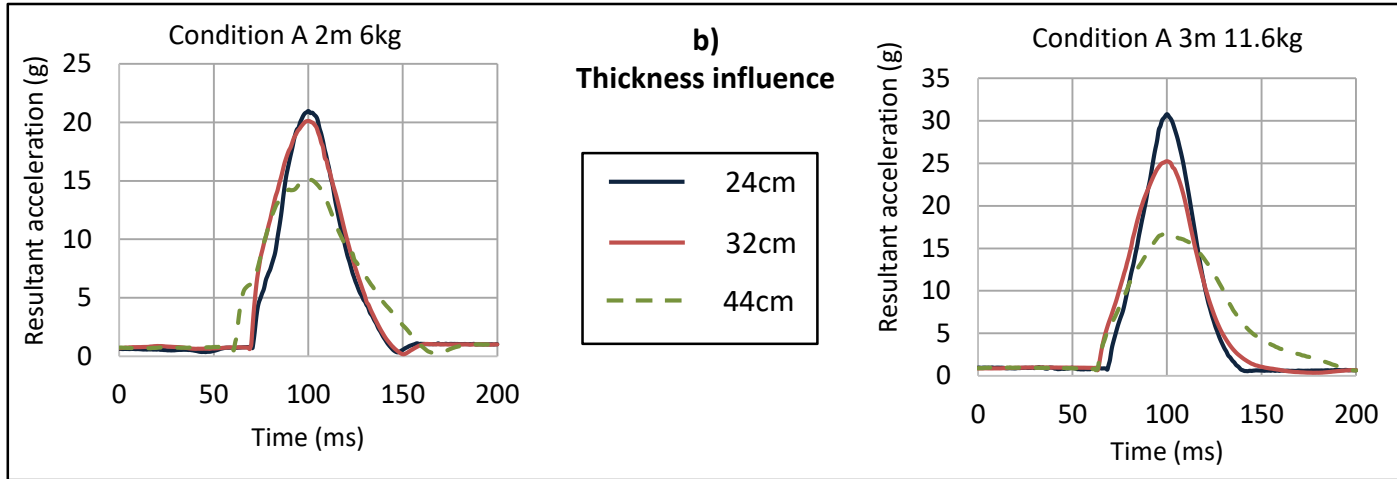
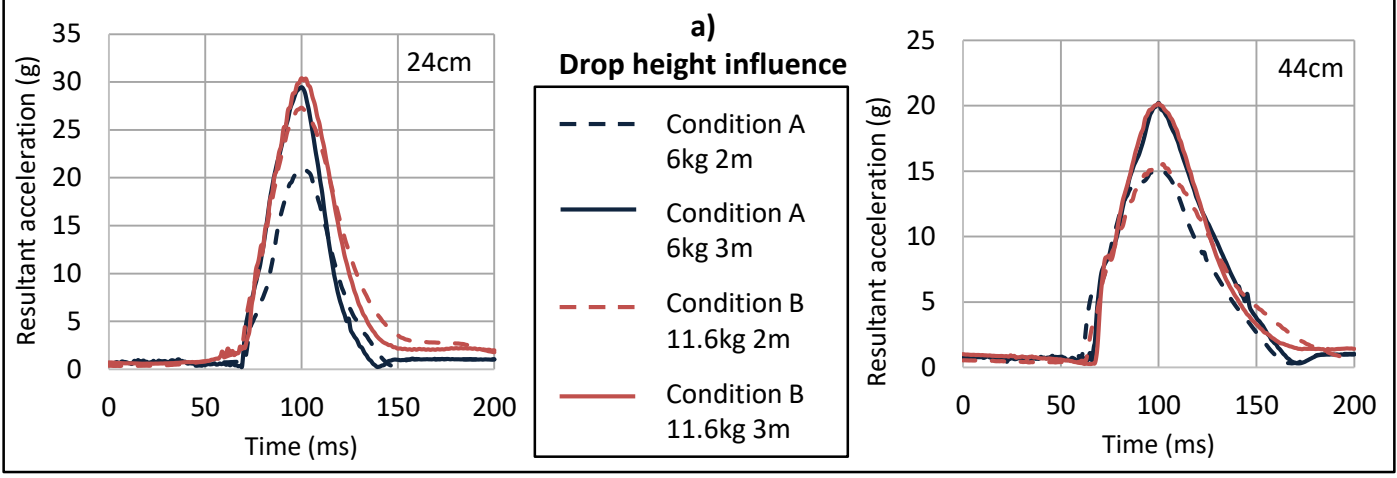
|           |         | Drop height |   |
|-----------|---------|-------------|---|
|           |         | 2m          | 3m  |
| Head mass | 6kg     | condition A | condition A<br>condition B<br>condition C |
|           | 11.6 kg | condition B | condition A<br>condition B                |

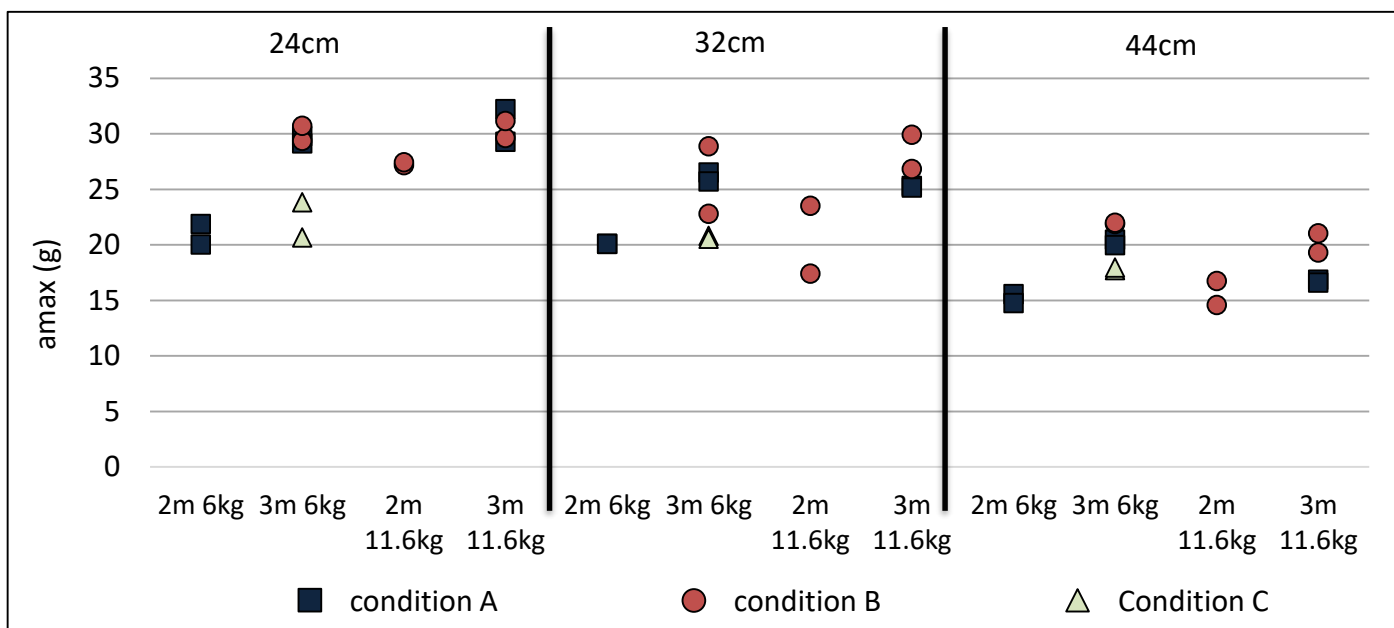
c)



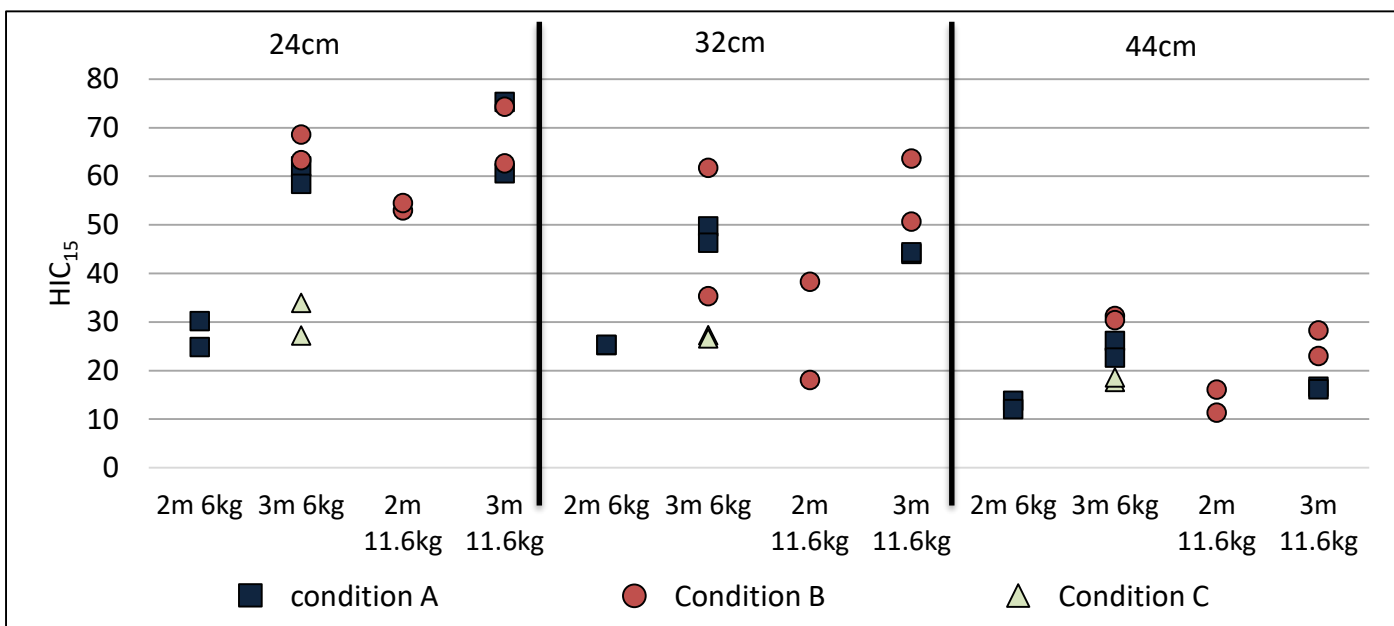
d)







a)



b)