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1 **Collisions against obstacles while skiing: which users for which impact conditions?**

2
3 **Collisions contre obstacles en ski alpin : profils et conditions d'impact**

4
5 Short title: Collisions against obstacles while skiing: users and impact conditions

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20
21 **DISCLOSURE OF INTEREST**

22 The authors declare that they have no competing interest.

24 **COLLISIONS AGAINST OBSTACLES WHILE SKIING: WHICH USERS FOR**
25 **WHICH IMPACT CONDITIONS?**

26
27 **COLLISIONS CONTRE OBSTACLES EN SKI ALPIN : PROFILS ET CONDITIONS**
28 **D'IMPACT**

29
30 **ABSTRACT**

31 **Objective:** despite their potential severity, collisions against obstacles on alpine ski slopes
32 remain poorly described and a better understanding of these accidents is required to improve
33 the protection of users on the slopes. Therefore, this study aimed to characterize the impact
34 conditions applied to the human body during collisions against obstacles by coupling multibody
35 simulations while skiing with an epidemiological analysis to model representative scenarios.

36 **Equipment and methods:** in France, between 2014 and 2019, 201805 snow sports accidents
37 led to ski patrol interventions and/or ski resort doctors' consultations. The 3393 collisions
38 against obstacles included in these accidents were analyzed (population, injuries, accident
39 conditions). Based on this characterization, 1080 multibody simulations of collisions against
40 obstacles were performed. They included various skier speed and size, slope angle, obstacle
41 type and distance at impact to better understand loading conditions applied to the human body.

42 **Results:** victims of collisions against obstacles were frequently skiers, young people, wore a
43 helmet and head/neck and trunk were injured in up to 46% of the accidents. The numerical
44 simulations confirmed head protection as a priority, due to the high frequency of head impacts
45 (68%), especially as the first impact location (47%), associated with high normal impact speeds
46 (30 ± 15 km/h). Trunk impacts (63% of the accidents) also appeared at risk. Moreover, the
47 initial speed and the distance to the obstacle are two key factors influencing impact severity and
48 should be considered in the slopes' layout. Thus, this work provided an original epidemiological
49 characterization of victims of collisions against obstacles and of their injuries. The large
50 database of numerical simulations identifies the impact conditions of representative accidents.
51 These data and impact conditions are key elements for the evaluation and design of safety
52 mattress, for standards revision, for slopes' layout, for the reconstruction of a specific collision
53 against obstacle and for the evaluation of the potential severity of such accidents.

56 **RÉSUMÉ**

57 **Objectif** : malgré leur sévérité potentielle, les collisions contre obstacles survenant sur les
58 domaines skiabiles alpins demeurent peu étudiées et une meilleure compréhension de ces
59 accidents est requise afin d'améliorer la protection des usagers fréquentant les domaines
60 skiabiles. Ainsi, cette étude vise à caractériser les conditions d'impact subies par le corps humain
61 lors de collisions contre obstacles en associant des simulations multi-corps avec une analyse
62 épidémiologique permettant de modéliser des scénarios d'accidents représentatifs. **Matériels**
63 **et méthodes** : en France entre 2014 et 2019, 201805 accidents de sports d'hiver ont mené à une
64 intervention des pisteurs-secouristes et/ou à une consultation dans un cabinet médical en station.
65 Les 3393 collisions contre obstacles incluses dans ces accidents ont été analysés (population,
66 blessures, conditions d'accident). Puis 1080 simulations multi-corps de collisions contre
67 obstacles ont été réalisées à partir de cette caractérisation épidémiologique. Elles comprenaient
68 différentes vitesses et morphologies de skieurs, pentes de piste, types et distances jusqu'à
69 l'obstacle afin de mieux comprendre les conditions d'impact appliquées au corps humain.
70 **Résultats** : les victimes des collisions contre obstacles étaient souvent des skieurs, des
71 personnes jeunes, qui portent un casque et jusqu'à 46% des accidents ont induit des blessures
72 aux régions tête/cou et torse. Les simulations numériques ont confirmé la nécessité de cibler la
73 protection de la tête, de par la forte fréquence des impacts de la tête (68%), en particulier en
74 première région d'impact (47%), et des vitesses d'impact normales élevées (30 ± 15 km/h). Les
75 impacts du torse (63% des accidents) sont également à risque. De plus, la vitesse initiale du
76 skieur et la distance avant l'obstacle sont deux paramètres influençant la gravité de l'impact et
77 devraient être pris en compte dans l'aménagement des pistes. Ainsi, cette étude apporte une
78 caractérisation épidémiologique des victimes des collisions contre obstacles et de leurs
79 blessures. La grande base de données de simulations numériques a également permis
80 d'identifier les conditions d'impacts d'accidents représentatifs. Ces données et conditions
81 d'impact sont essentielles pour l'évaluation et la conception des matelas de protection, pour la
82 révision des normes, pour l'aménagement des pistes, pour la reconstruction d'un accident précis
83 et pour l'évaluation de la gravité potentielle de ces accidents.

84

85 **KEYWORDS**: snow sport; biomechanics; epidemiology; computer simulation; safety

86 **MOTS CLÉS** : sport d'hiver ; biomécanique ; épidémiologie ; simulation numérique ; sécurité

87

88 **1. Introduction**

89 Collisions against obstacles (CO) represent around 1% of ski patrol interventions on French ski
90 slopes [1] and 4.5% of the accidents on ski slopes in the USA [2]. However, they are a major
91 safety issue on ski slopes as they can lead to severe traumatic brain injuries (TBI) [3], and deaths
92 on ski slopes (from 35% to more than 70% according to Ruedl et al. [4] and Shealy et al. [5]).
93 Despite this potential severity, CO are poorly described. CO were mostly mentioned as accident
94 type but the analyses were not focused on them. Dedicated studies on CO were conducted more
95 than 30 years ago [6,7] and snow sports activities have evolved a lot since, through equipment,
96 population and behavior on ski slopes. Most of the more recent studies either focused on global
97 epidemiological analysis [2] or specific accident severity (such as deaths on slopes [4,5]), or
98 specific injury location (like head injuries [3]). Head impact conditions and the risk evaluation
99 of head injury were focused for various scenarios of CO while skiing through human multibody
100 simulations [8]. Nevertheless, impact conditions on other body segments during these CO
101 remain unknown.

102
103 Nowadays, in regards to injury severity up to fatal accidents observed on ski slopes, CO
104 prevention is becoming a key point for ski resorts. It is also illustrated by numerous safety
105 equipment placed in skiing areas on or close to obstacles to protect users from a collision against
106 them and by many questions rising about the efficiency of such devices. The performances of
107 safety equipment dedicated to CO protection are addressed through existing regulation
108 standards (NF S52-105 French standard for safety mattresses [9]). The safety performances of
109 these devices were also investigated by some studies [10,11]. However, there is little data
110 available on CO (impact speed, impact location and injuries caused), the consistency between
111 normative impact conditions and the reality of impacts on ski slopes is asked.

112
113 Hence the main research question who thrust this work was about the need to get a better
114 comprehension of CO. Therefore, this study aimed at providing a description of the impacts of
115 collisions against obstacles in snow sports by combining epidemiological data investigations
116 and numerical simulations to investigate the most relevant accident scenarios. The final
117 objective of this work was to provide a relevant description of the impact conditions (velocity
118 and location) applied to the human body during a CO.

119
120

121 2. Materials and methods

122 2.1. Epidemiological analysis

123 Medical and ski patrol networks are powerful tools to provide robust data for an
124 epidemiological analysis of accidents on ski slopes. In France, three entities deal with snow
125 sport accidents: the doctors in ski resort medical offices [12], the ski patrollers [1] and the
126 doctors in hospitals in the valleys. None of these groups sees the entire injured population: the
127 most severe accidents leading to a direct transfer to the hospital are seen by ski patrollers and
128 hospital doctors but not by ski resort doctors. The less severe accidents, where the users (skiers
129 or snowboarders) go by themselves to the medical centers are only seen by ski resort doctors.
130 And for other accidents, users are brought to ski resort medical offices by ski patrollers (around
131 40% of the medical office consultations [12]).

132
133 Thus, to provide a complete comprehension of CO, the analysis was based on two databases:
134 1) the one of the *Association des Médecins de Montagne* (database-Mdm) and 2) the one of the
135 *Système National d'Observation de la Sécurité en Montagne* (SNOSM) (database-Snosm). The
136 *Association des Médecins de Montagne* is a 29 years old network of doctors located in 14
137 French ski resorts which gathers epidemiological information on snow sports. The *SNOSM*
138 collects ski patroller accident reports from 60 ski resorts in French mountains. The two
139 networks publish annual syntheses on snow sport epidemiology [1,12] and scientific
140 publications were based on the database-Mdm [13,14]. This double approach allowed an
141 exhaustive analysis of snow sport accidents as firstly, the two networks formed one of the
142 largest databases on snow sports accidents in the world with more than 200 000 accidents
143 between 2015 and 2019 (88 451 among the database-Mdm and 113 354 among the database-
144 Snosm) for an incidence of 2.68 accidents per 1 000 skier days in 2019 based on the database-
145 Mdm [12]. Secondly, this double analysis included all accidents requiring an immediate
146 treatment, through medical consultation or ski patrol rescue. Thus, it brought an exhaustive
147 analysis on the injured population on our slopes.

148
149 The analysis was conducted on skiing and snowboarding accidents occurring on French ski
150 areas from the winter seasons 2014-2015 to 2018-2019 and restricted to accidents with a well-
151 defined accident type (CO, collisions against another user or non-collisions). Accident different
152 than CO were only used to compute the occurrence of CO among snow sports accidents. 88 451
153 and 113 354 accidents from the database-Mdm and the database-Snosm were analyzed. Among
154 them, CO were identified by the variable "Collision with = obstacle" for the database-Mdm and

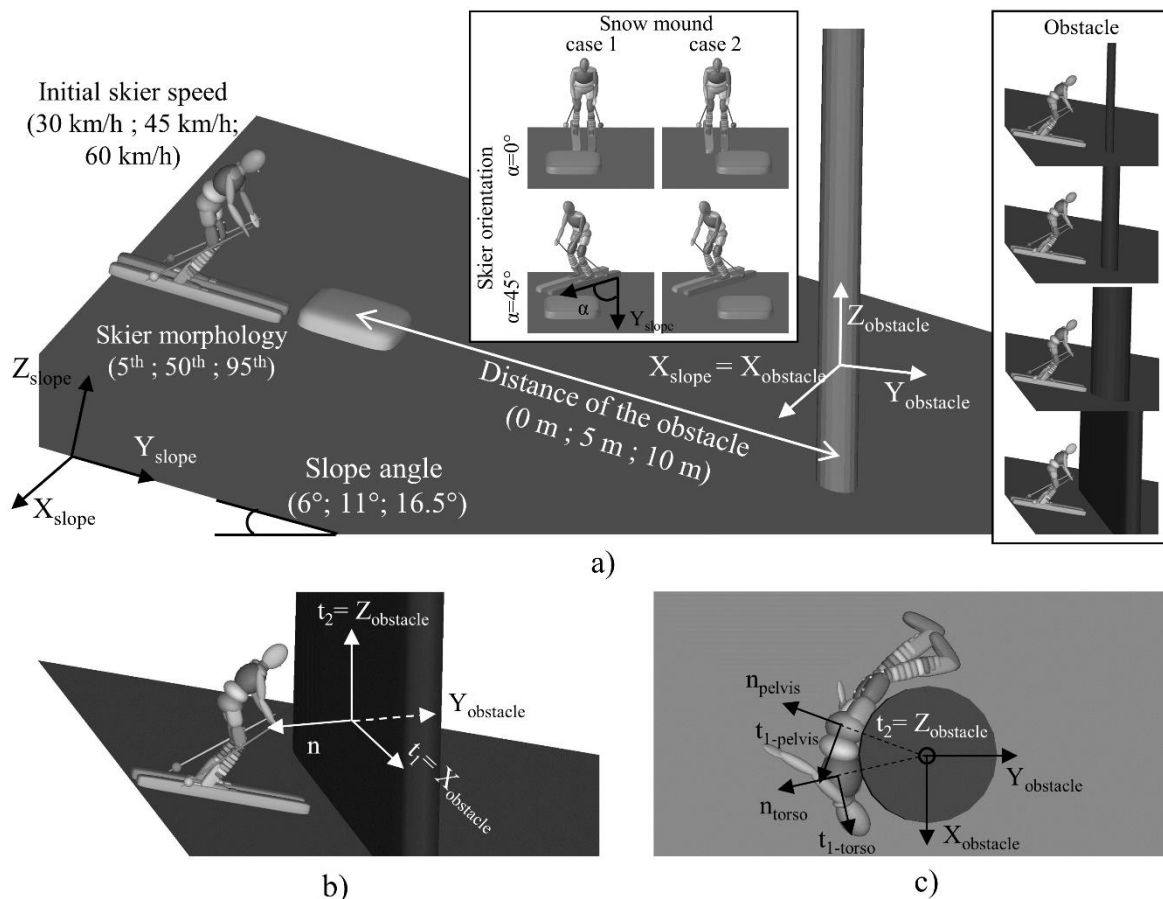
155 by the information included in three free-text fields related to accident type, accident cause and
156 collision type for the database-Snosm. Two groups were considered: CO from the database-
157 Mdm (n=2 570) and CO from the database-Snosm (n=823). Age, gender, type of sport practiced
158 and injury location were investigated for all accidents. For injury location, five anatomical
159 regions were considered: *head/neck* (including head, neck and cervical spine), *trunk* (thorax,
160 abdomen, pelvis/hip, and spine), *upper limbs* (arm, elbow, forearm, wrist, hand, thumb,
161 shoulder and clavicle), *knee* and *lower limbs* (thigh, leg, ankle and foot). Multiple injuries were
162 counted once and recorded according to their anatomical region if they occurred on the same
163 one or as *multiple* if they occurred on two or more anatomical regions (except for the
164 combination of a knee injury and a lower limb injury, which was only recorded as lower limb
165 injury). The database-Snosm also provided additional information on the location of the
166 accident. Moreover, information on the self-estimated level (SEL) of the user, the use of a
167 helmet or back protector and the type of injury, was included in the database-Mdm. The analysis
168 focused on describing the victims of CO, the location of CO and the injuries induced to then
169 numerically model representative accident scenarios.

170

171 **2.2. Model description**

172 An existing multibody human model, previously developed for pedestrian accident analysis and
173 adapted for snow sports accidents [8], was used to model CO on Madymo 7.5 (Tass
174 International, Helmond, Netherlands) (Figure 1). Based on the epidemiological analysis, only
175 CO occurring while skiing were modelled and various CO scenarios were investigated with a
176 design of experiment (DOE, Figure 1a). For that, three morphologies of a male skier were
177 investigated: a 5th percentile, a 50th percentile and a 95th percentile (described, along with their
178 equipment, by Bailly et al. [8]), with an initial skier speed of 30 km/h, 45 km/h and 60 km/h,
179 corresponding to the mean speed \pm standard deviation on ski slopes [15]. The slope angle was
180 adapted to represent three slopes: very easy, easy and medium slopes, with respective angles of
181 6°, 11° and 16.5° [16]. We assumed that the ski slope was covered in hard snow (using
182 previously calibrated snow properties [17], friction coefficient of 0.3 against the skier and 0.09
183 against the skis). In cases of TBI induced by a CO, 31% of the CO were characterized by a
184 direct collision between the user and the obstacle, but in 69% of CO, the user fell prior to the
185 obstacle and the fall was followed by a CO [3]. Therefore, these two scenarios were modelled:
186 1) direct collision and 2) collision after a fall. The fall was generated by the impact of skis
187 against a snow mound, located either 5 m or 10 m before the obstacle. The position of the snow
188 mound in relation to the skiers was also varied for each skier's position to simulate different

189 fall kinematics. Two skier positions were modelled: either facing the slope or with a 45°
 190 orientation (Figure 1a). Three cylindrical obstacles (with diameters of 20 cm, 40 cm and 90 cm)
 191 and a flat obstacle were modelled. The obstacle was considered as rigid. The full factorial DOE
 192 was conducted with HyperStudy 2017 (Altair, Troy, Michigan, USA), leading to 1080
 193 simulations.
 194



195
 196 **Figure 1.** a) Multibody model and parameters of the design of experiment, b) definition of the
 197 normal (n) and tangential (t₁ and t₂) directions in case of a flat obstacle and c) in case of a
 198 cylindrical obstacle

199

200 2.3. Variables of interest and analysis

201 The objective of the DOE was to define the impact conditions (contact areas and impact
 202 velocities) of the human body against the obstacle during the CO. Therefore, contacts between
 203 body segments (head, neck, torso, abdomen, pelvis, shoulders, left and right arms, forearms,
 204 hands, thighs, legs and ski boots) and the obstacle were investigated. Special attention was paid
 205 to the first impact between the skier and the obstacle. Impact speeds were investigated through
 206 normal, tangential and resultant speeds expressed in the obstacle coordinate system. The normal

207 direction (n) of the obstacle was obvious for the flat obstacle (Figure 1b), but this direction
 208 needed to be computed for cylindrical obstacles given the obstacle position and the position of
 209 the center of mass of the body segment prior to the impact (Figure 1c). Therefore, the normal
 210 direction was unique for each body segment and was not aligned with the slope (Y_{slope}) nor the
 211 skier's initial velocity. Tangential speeds were expressed in the plane normal to the impact
 212 direction (formed by vectors t_1 and t_2 on Figure 1b and 1c).

213

214 Epidemiological and numerical results were post-processed with Matlab 2013a (MathWorks,
 215 Natick, Massachusetts, USA) and R (R Core Team (2015), Vienna, Austria).

216

217 3. Results

218 3.1. Epidemiological analysis

219 From 2014-2015 to 2018-2019, 88 451 and 113 354 alpine snow sport accidents were recorded
 220 respectively in the database-Mdm and database-Snosm, considering all accidents types and
 221 severities. Among them, 2 570 (2.9%) and 823 (0.7%) were identified as CO in these two
 222 databases (Table 1). Victims were mostly young (mean age < 30 years old), experienced, skiers
 223 (>85%), wore helmets (70%) but no back protectors (87%), and males were slightly more
 224 represented than females. Moreover, the majority of patients went to medical offices without
 225 ski patrol rescue (65%). CO mostly occurred on slopes (77%), particularly on easy (35%),
 226 medium (20%) and very easy slopes (13%).

227

228 **Table 1.** Characterization of victims and injuries induced by CO among the databases

		database-Mdm n=2 570 n (%)	Database-Snosm n=823 n (%)
Gender	Male	1 592 (62)	466 (57)
	Female	935 (36)	350 (43)
	Unknown	43 (2)	7 (1)
Age (years)	≤19	979 (38)	402 (49)
	20-39	889 (35)	216 (26)
	40-59	536 (21)	150 (18)

	≥60	166 (6)	36 (4)
	Unknown	-	19 (2)
	Mean ± SD	29.2 ± 17.0	25.4 ± 17.3
Sport	Alpine skiing	2 172 (85)	760 (92)
	Snowboarding	396 (15)	63 (8)
	Other	2 (0)	-
SEL	Beginner	317 (12)	
	Intermediate	1 032 (40)	
	Confirmed	1 024 (40)	
	Professional	50 (2)	
	Unknown	147 (6)	
Helmet	Yes	1 811 (70)	
	No	716 (28)	
	Unknown	43 (2)	
Back protector	Yes	162 (6)	
	No	2 235 (87)	
	Unknown	173 (7)	
Ski patrol rescue	Yes	890 (35)	
	No	1 669 (65)	
	Unknown	11 (0)	
Injury location	Head/neck	588 (23)	185 (22)
	Trunk	440 (17)	194 (24)
	Knee	519 (20)	70 (9)
	Lower limbs	297 (12)	154 (19)
	Upper limbs	680 (26)	88 (11)

	Multiple injuries	46 (2)	71 (9)
	Unknown	-	61 (7)
Injury type	Fracture	503 (20)	
	Contusion	903 (35)	
	Sprain	473 (18)	
	Luxation	50 (2)	
	MTL	114 (4)	
	Laceration	451 (18)	
	TBI	69 (3)	
	Unknown	7 (0)	
Accident location	On slopes		630 (77)
	Off trails		55 (7)
	Lifts		100 (12)
	Other/unknown		38 (5)
Slope's type	Very easy		104 (13)
	Easy		284 (35)
	Medium		161 (20)
	Expert		37 (4)
	Terrain park		10 (1)
	Other/unknown		227 (28)

229 *SD: Standard Deviation, MTL: Musculo-Tendinous Lesion*

230 All body regions were affected by CO but more than 40% of the accidents led to head or trunk
231 injuries (two regions being associated with neurological or hemorrhagic issues). 9% of the CO
232 of the database-Snosm caused injuries to more than one anatomical region. Among all injuries,

233 contusions were the most frequent (35%), followed by fractures (20%), lacerations (18%) and
234 sprains (18%).

235

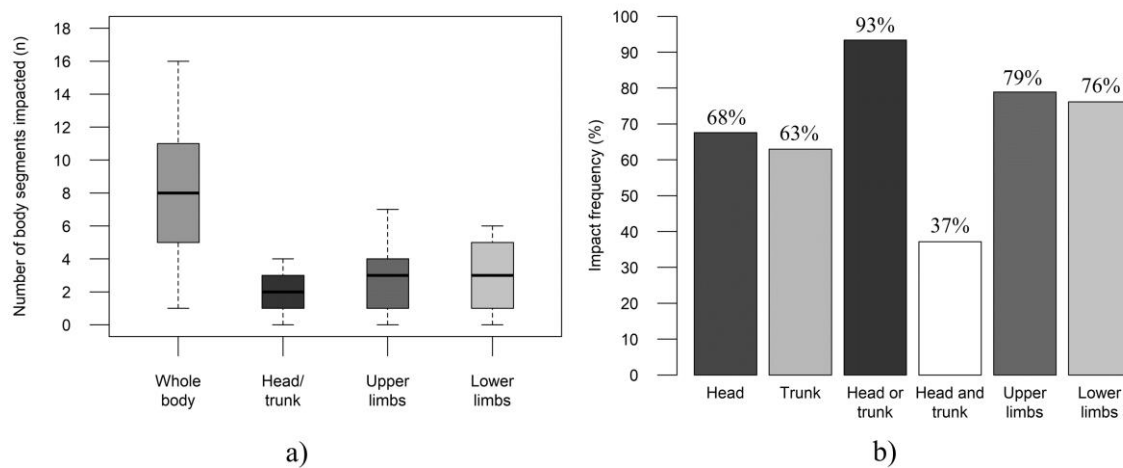
236 3.2. Multibody analysis

237 Among the 1 080 simulations, 170 did not induce a collision between the skier and the obstacle
238 because the skier's fall stopped before impacting the obstacle. These scenarios were
239 characterized by far obstacles and low initial skier speeds (respectively 147 and 152 simulations
240 with an obstacle at 10 m and an initial speed of 30 km/h including 129 simulations with both a
241 far obstacle and a low initial speed).

242

243 For the other 910 simulations, 8 ± 4 body regions (out of 18 possible) impacted the obstacle
244 (Figure 2a). All body areas were targeted by these impacts, though no impact occurred to the
245 neck. In 93% (respectively in 37%) of accidents, at least one impact occurred between the
246 obstacle and the head or (respectively and) the trunk (Figure 2b). Finally, the head was the first
247 body region to impact the obstacle in 47% of accidents, followed by ski boots (17%) and hands
248 (15%). Without distinction of the impact order, the head remained the body region impacting
249 the obstacle the most, before the pelvis, shoulders and thighs.

250



251

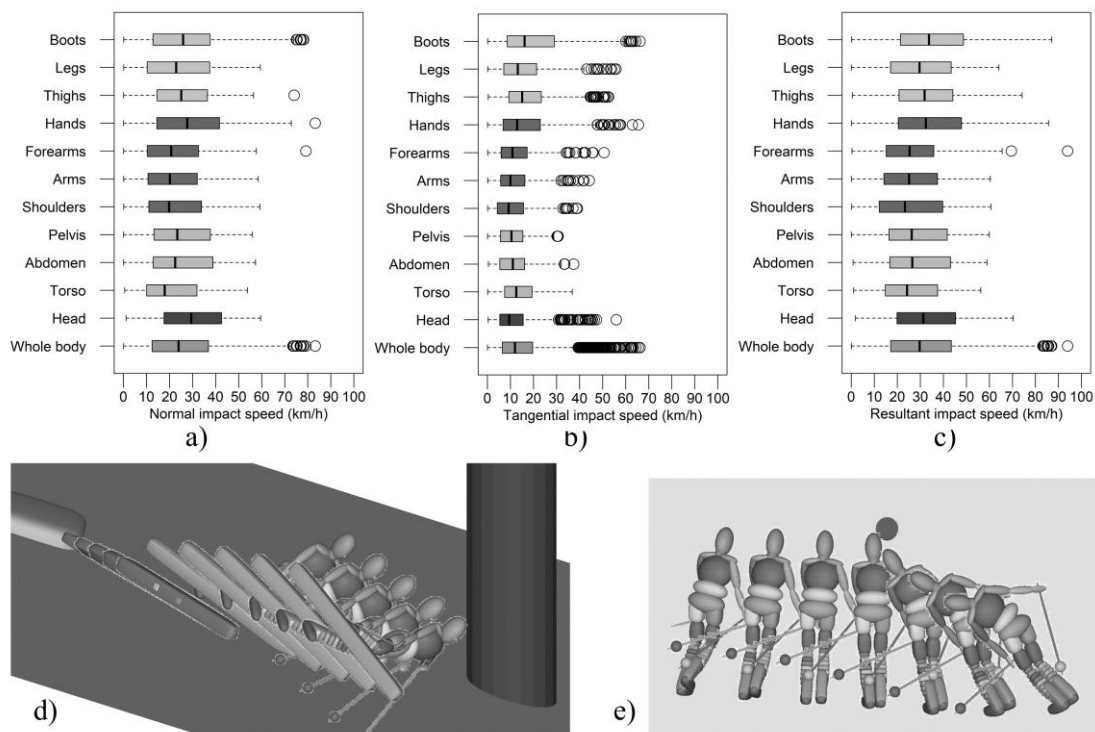
252 **Figure 2.** a) Number of body segments impacted, b) number of simulations (normalized by the
253 total number of simulations: 910) leading to at least one impact between the obstacle and the
254 body region

255

256 Considering all impacts between the skier and the obstacle, normal speeds (25.3 ± 15.7 km/h)
257 were higher than tangential speeds (14.4 ± 10.6 km/h) (Figure 3a and Figure 3b). Normal speeds

258 were higher for the head (30.0 ± 14.8 km/h) and the hands, followed by the lower limbs,
 259 abdomen and pelvis (Figure 3a), whereas higher tangential speeds were recorded for ski boots,
 260 hands and thighs than for the rest of the body (Figure 3b). Finally, the lower limbs, hands and
 261 head were the body regions impacting the obstacle with the highest resultant speeds (Figure
 262 3c). For head impacts, some tangential speeds were very high compared to the rest of the speed
 263 distribution and appeared as outliers (7.6% of the head tangential speeds). These high values
 264 were mostly caused by the downward motion of the head during the fall (Figure 3d) or by the
 265 sliding motion of the head against the obstacle (Figure 3e).

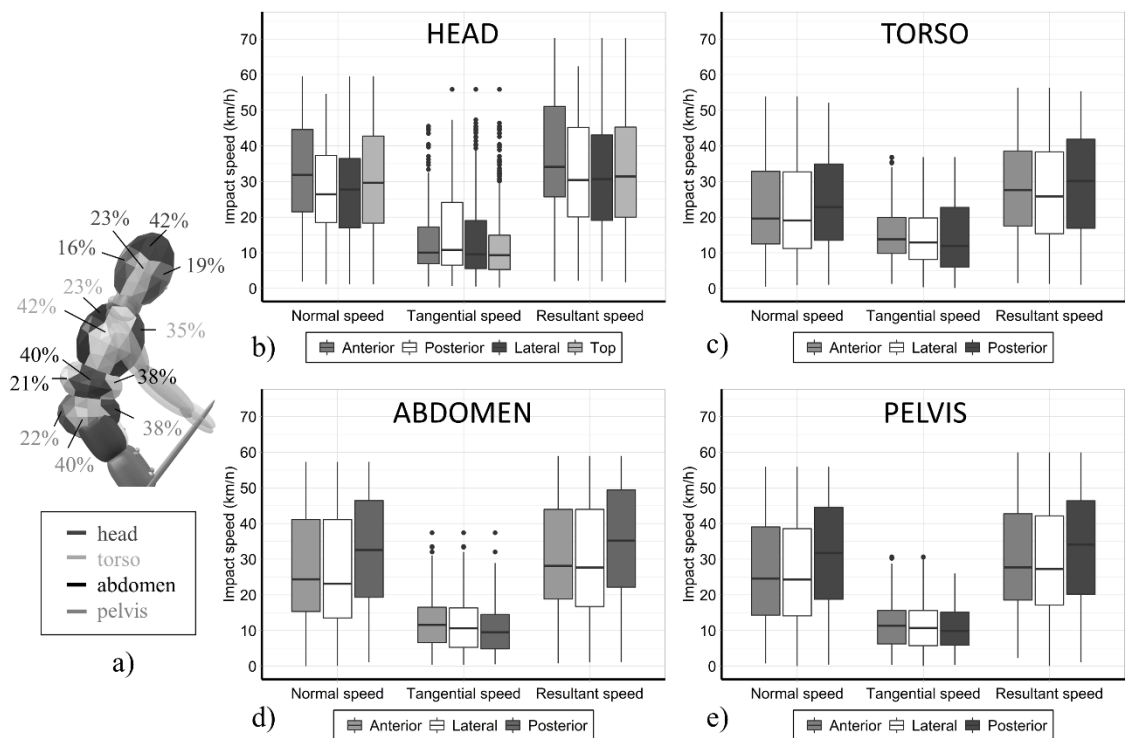
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 267



268
 269 **Figure 3.** Distribution of a) normal impact speeds, b) tangential impact speeds, c) resultant
 270 impact speeds, d) case of tangential speed induced by the downward motion of the head and e)
 271 case of a sliding motion of the head compared to the obstacle

272
 273 Head and trunk impacts were focused on Figure 4 by considering all impacts on their subareas.
 274 The top of the head was the head area impacting the obstacle the most, with a high normal
 275 speed. Anterior (respectively posterior) head impacts were less frequent but associated with
 276 high normal and resultant (respectively tangential) speeds. Most of trunk impacts occurred on
 277 anterior and lateral areas though the higher impact speeds were recorded on posterior areas.

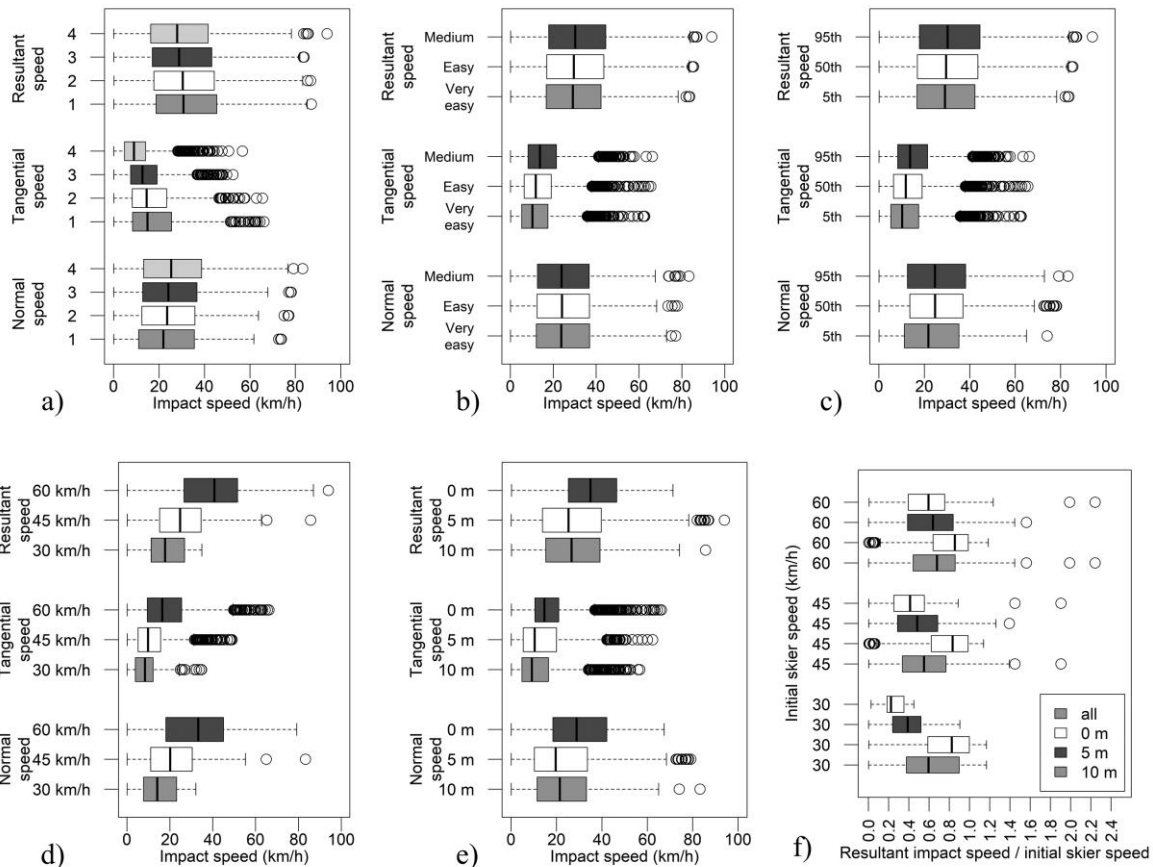
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279
 280 **Figure 4.** a) impact frequencies of head and trunk according to areas of interests and including
 281 multiple impacts, and b) head, c) torso, d) abdomen and e) pelvis impact speeds according to
 282 the areas of interest.

283
 284 The type of obstacle, type of slope and the skier's size had little influence on impact velocities
 285 (Figure 5a, b and c) whereas the initial speed and the distance of the obstacle strongly affected
 286 normal, tangential and resultant impact speeds (Figure 5d and e). First, skiers travelling at 30
 287 km/h, 45 km/h and 60 km/h respectively impacted the obstacle at resultant speeds of 18.2 ± 9.1
 288 km/h, 25.1 ± 12.7 km/h and 38.7 ± 16.8 km/h, which corresponded on average to 61%, 56%
 289 and 65% of their initial speed. Second, the fall of the skier (when the obstacle was placed at 5
 290 m or 10 m) induced a strong reduction of the impact speeds, compared to direct collisions
 291 (distance of 0 m). As these two factors also had a strong influence on the absence of impact
 292 between the skier and the obstacle, their interaction was investigated in Figure 5f. For high
 293 initial speeds, a higher proportion of the initial speed was kept at impact (62% and 57% on
 294 average for 5 m and 10 m at 60 km/h) than for low initial speeds (respectively 38% and 25% at
 295 30 km/h, Figure 5f). This interaction was absent for direct collisions (0 m) for which body
 296 segments impacted the obstacle on average at 77% of the initial skier speed.

297



298
 299 **Figure 5.** Speed distribution of all impacts according to a) the shape of the obstacle (a cylinder
 300 with a diameter of 1: 20 cm ; 2: 40 cm ; 3: 90 cm ; and 4: a flat obstacle), b) the slope, c) the
 301 skier’s size, d) the initial skier speed, e) the distance of the obstacle (direct collision (0 m) or
 302 collision after a fall (5 m or 10 m)) and f) distribution of the resultant impact ratio (resultant
 303 impact speed normalized by the initial speed) according to initial speed and obstacle distance
 304

305 **4. Discussion**

306 The objective of this article was to describe the impact conditions of CO on ski slopes in terms
 307 of impact speed and injury location. The originality and reliability of this work come from the
 308 combination of exhaustive epidemiological data and a large number of numerical simulations
 309 in order to investigate various possible CO.

310

311 **4.1. Epidemiological analysis**

312 This epidemiological analysis of CO aimed at providing an exhaustive representation of these
 313 accidents through the double analysis of both ski patroller and ski resort doctor databases. This
 314 double investigation was particularly interesting as it includes all accident severities requiring
 315 an immediate intervention from the mild accident to the life-threatening one helicoptered

316 towards hospital. Moreover, this analysis identified collisions against obstacles among two
317 large databases, regrouping more than 200 000 accidents. This favors the study of a
318 representative population of CO and a powerful analysis. The interest of analyzing both ski
319 patrol rescues and medical consultations is highlighted by the low rate of ski patrol rescue
320 among CO victims from the database-Mdm (around one third). This element also underlines
321 the heterogeneity of the severity of these accidents: though CO can be severe and lethal, most
322 of CO victims were able to go to the medical center by themselves, without ski patrol rescue.
323 The double analysis also brought complementary information on these accidents which
324 participates to this exhaustive analysis. The database-Snosm covered all aspects of the accidents
325 (victims, injuries, accident location and rescue services) while the database-Mdm brought
326 detailed information on victims and their injuries. The two databases provided consistent
327 information (young age of the victims, majority of skiers, and high occurrence of injuries to the
328 head/neck or the trunk) which reinforces the reliability of this analysis. This exhaustive analysis
329 was associated with some redundancy as CO victims rescued by ski patrol and brought to
330 medical offices were included in the two databases.

331

332 This description of CO on French ski slopes was consistent with previous studies, concerning
333 the frequency of CO (0.7-2.9% vs 4.5% of ski patrol interventions in the USA [2]) but also the
334 injury locations. Indeed, head/neck and trunk were frequently injured, as previously observed
335 by Lystad [7] (around 26% of head and 23% of trunk injuries), which highlighted the potential
336 severity of CO, as the most life-threatening injuries occurred in these areas of the body. Injuries
337 were similar to Lystad's study (who observed around 57% of contusions, 27% of fractures, 7%
338 of lacerations and 4% of sprains) [7] but with more lacerations (18%) and sprains (18%) and
339 fewer contusions (35%) and fractures (20%). Besides, the occurrence of TBI among CO victims
340 (3%) might be underestimated compared to the 10% observed by Bailly et al. [13], probably
341 due to the inclusion of skull fractures and concussions in the TBI group of this latter study. This
342 analysis of numerous CO (3 393 CO over 201 805 accidents on ski slopes), combined with a
343 consistency between the two databases and with previous studies provided a solid basis for
344 numerical CO modelling. In particular, this description highlighted the need to focus on alpine
345 skiing CO, on medium or easier slopes, inducing head or trunk injuries. These elements should
346 be targeted by evolutions on CO protection.

347

348 **4.2. Numerical modelling**

349 The CO description (population at risk, accident location) of the epidemiological analysis was
350 used to investigate the impact conditions of CO by modelling various accidents scenarios. To
351 represent the variability of obstacles found on or close to ski slopes, four obstacles were
352 modelled: a post, a tree, a lift tower and a wall. This study aimed at defining impact conditions
353 against obstacles to then improve the preventive measures taken against these accidents
354 (including through safety devices). Thus, protection devices were not modelled, and the
355 obstacles were assumed to be rigid bodies, given the high difference in stiffness between the
356 human body and a tree or a lift tower. Little information was available on the CO kinematics
357 and on the possible fall prior to the obstacle, so we chose to model various accident scenarios
358 through different fall initiations (through the combination of the skier orientation and the
359 position of the snow mound). Some scenarios remain to be investigated, such as CO after or
360 during a jump or CO after a short fall (less than 5 m). We wished to weight the DOE according
361 to the accident frequencies to bring the analysis closer to the accident reality but it was not
362 possible due to the lack of information on the obstacle type and distance, the skier's size or the
363 accident's kinematics. All impact speeds were analyzed independently of the impact order, as
364 the first impact did not ultimately have the most severe consequences (for example, a hand
365 impact followed by a head impact). These impact speeds were defined in the coordinate system
366 of the obstacle, to characterize the impact conditions applied to protection devices. Therefore,
367 the normal direction was not aligned with the initial speed, leading to potential high tangential
368 impact speeds. Higher normal speeds compared to tangential speeds were a severity factor, as
369 higher energies were dissipated against the rigid obstacle than in case of sliding. However, the
370 obstacle was numerically placed on the skier's way to ensure the modelling of the collision,
371 which represented worst-case situations and may have induced an overestimation of the normal
372 speed contribution. Still, this numerical analysis brought the first description of impact areas
373 and impact speeds of CO based on representative accident conditions. Furthermore, the
374 numerous simulations constitute a large database on CO than can be useful for prevention
375 measures and accident reconstructions.

376

377 **4.3. Impact conditions**

378 This study highlighted the need to protect head impact during a CO. Indeed, this body region,
379 at risk of life-threatening injuries, frequently impacted the obstacle (68% of the accidents) and
380 especially in first position (47%). This high impact frequency was linked to the kinematics of
381 the skier, with either a forward fall or the initial position of the skier in case of direct collisions.
382 This induced high impact speeds, high energy dissipations on the head and therefore high injury

383 risks. These head impact speeds were consistent with a previous study [8], though higher
384 tangential velocities were previously obtained, probably due to different modelling choices
385 (distance, orientation and type of obstacle and approach angle of the skier). Besides, most of
386 head impacts occurred on the top, the lateral or the posterior areas of the head, areas that are
387 protected by a helmet (wore in 70% of CO, based on the epidemiological analysis). This might
388 reduce the severity of the impact. However, high normal impact speeds were recorded on the
389 anterior area of the head which is not protected by the helmet and thus, at risk of face injuries.
390 Trunk impacts also need to be protected due to their impact frequency (63% of the accidents)
391 combined with the life-threatening risks associated with this body region. These results are also
392 consistent with the high frequency of head and trunk injuries observed in the epidemiological
393 analysis. Most of impacts occurred in the antero-lateral trunk and thus, were at risk of
394 hemorrhagic injuries whereas the less frequent but more violent posterior impacts were more
395 likely to cause neurologic injuries. Further analyses are required to investigate the injury risks
396 of such accidents. The impact speeds of hands and ski boots against the obstacle were also high.
397 However, their masses and inertias were low and offset compared to the mass distribution of
398 the whole body. Thus, hand or boot impacts were more likely to deflect the skier during the
399 collision than to stop it, contrary to trunk impacts. Besides, hand and foot impacts are not at
400 risk of life-threatening injuries, therefore the protection of head and trunk impacts should be
401 the primary concern of CO safety devices.

402

403 **4.4. Standards' evolution**

404 These new elements on CO impact conditions provide inputs for mattress testing conditions. In
405 keeping with the French standard, mattresses are tested with impacts at 9.3 and 19.5 km/h [9]
406 which corresponded to the 18th and 41th percentiles of all the normal impact speeds obtained
407 while considering representative initial skier speeds. Therefore, the standards should include
408 impact tests at higher impact speeds. Besides, the two impacting masses of this standard are
409 small (diameter inferior to 20 cm). This does not represent the reality of CO as 1) large body
410 regions (such as the trunk) were identified as primary concern and 2) numerous body segments
411 impacted the obstacle during an accident, which led to high contact surfaces. Based on the
412 epidemiological and numerical analyses, we recommend including both head-like and trunk-
413 like impacts in safety mattress evaluations, which also allow to evaluate protection devices in
414 two conditions: 1) small and piercing impacts and 2) large impact surface conditions.

415

416 **4.5. Obstacles' environment**

417 The initial impact speed combined with the distance of the obstacle are two major factors
418 associated with CO injury risks as they influenced 1) the absence of impact between the skier
419 and the obstacle but also 2) the impact speed (consistently with a previously study [8]). Direct
420 collisions between users and obstacles should be avoided as less energy is dissipated prior to
421 the impact with the obstacle, increasing impact speeds and accident severity. The lower speed
422 dissipation for high initial skier speed may be associated with the chosen obstacle distances.
423 However, a high initial speed remains a strong injury risk factor. These elements could
424 influence the environment around obstacles on slopes, by either moving obstacles away from
425 the slopes when possible, or through slow-down barriers placed prior to the obstacles, to
426 decrease initial skier velocity and therefore the impact velocity. Contrary to Bailly et al. [8] for
427 head impacts, the slope angulation did not induce high variations of normal impact speeds,
428 probably due to the larger slope variations previously modelled (0°, 20° and 40°).

429

430 **4.6. Limitations**

431 Considering the epidemiological analysis, the presence of a protection device on the obstacle
432 was not mentioned in the two databases, which could influence the injuries induced. As the
433 analysis focused on accidents requiring an immediate treatment, it did not include the mild
434 accidents where the victim was neither rescued by ski patrol nor went to a medical center on
435 the ski resort but consulted a doctor outside the resort. The comparison of the epidemiological
436 results was also limited by the few studies targeting these accidents. Currently, no experimental
437 data of skiing accidents can be used to validate the skier numerical model. However, this model
438 was previously validated for snowboarding, pedestrian, cyclist and motorcycle accidents [17–
439 19] and used for skiing falls, CO and collisions with another user [8]. Moreover, muscle activity
440 was not modelled but the contribution of this activity was estimated to be small considering the
441 short impact duration. Besides, given the proportions of females and young people among CO
442 victims, additional simulations should be performed to represent the whole population injured
443 by CO. The influence of snow properties was not investigated and only a worst-case scenario
444 (hard snow) was modelled. Finally, a direct comparison between the epidemiological and the
445 numerical analyses was not possible due to missing information on the accident kinematics and
446 on the obstacle (protection, distance, type).

447

448 **5. Conclusion**

449 By combining accident data analysis and multibody simulations, this work provides an original
450 methodology to investigate a large panel of potential accident conditions.

451

452 Through a unique database of 3 393 accident scenarios from more than 60 ski resorts in France
453 and 1 080 numerical simulations performed, it was possible to get the first characterization of
454 CO since the 1990s. This characterization should be very useful to improve the safety of skiers:
455 the category of CO victims (mostly young people, skiers, with some experience) gives relevant
456 indications for future public awareness campaigns; with more than 40% of injuries located on
457 head and trunk, the efficiency of safety mattresses in regards to trauma severity should be a
458 major concern.

459

460 At last, from simulations and main impact conditions (velocities ...), it becomes possible to
461 provide characteristics for an exhaustive evaluation of safety mattress efficiency and then
462 promote further evolutions for existing safety standards.

463

464 **6. Practical applications**

465 First, the current analysis brings quantitative information on the potential severity of CO
466 injuries, based on the kinematics of the accidents. These knowledges are essential for ski resorts
467 to adapt their prevention measures but also to define the rescue services required for an accident.
468 Secondly, the existing French standard for safety mattresses shows limited representation of
469 CO impact conditions. Mountain professionals are in favor of the evolution of this non-adapted
470 standard. This standard should evolve to target head and trunk impact protection, with
471 representative impact velocities. The results of this study brought important information for
472 safety mattress companies, by identifying impact conditions of safety mattress. These
473 knowledges can therefore be used to evaluate safety mattress performances but also to develop
474 more efficient mattresses and afford a better protection for the tomorrow's mattress. Finally,
475 this study brings a methodological tool to reconstruct a CO for a legal expertise. In this context,
476 the results of the DOE can participate to the reconstruction by identifying the potential accident
477 scenario and the influence of initial parameters.

478

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482

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545 **FIGURES CAPTIONS**

546 All figures are 2-column fitting images.