Analysis of Injury Mechanisms in Head Injuries in Skiers and Snowboarders

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ABSTRACT

BAILLY, N., S. AFQUIR, J.-D. LAPORTE, A. MELOT, D. SAVARY, E. SEIGNEURET, J.-B. DELAY, T. DONNADIEU, C. MASSON, and P.-J. ARNOUX. Analysis of Injury Mechanisms in Head Injuries in Skiers and Snowboarders. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 1–10, 2017. **Purpose**: Mechanisms of injury and description of head impacts leading to traumatic brain injury (TBI) in skiers and snowboarders have not been extensively documented. We investigate snow sport crashes leading to TBI 1) to identify typical mechanisms leading to TBI to better target prevention measures and 2) to identify the injury mechanisms and the head impact conditions. **Methods**: The subjects were skiers and snowboarders diagnosed of TBI and admitted between 2013 and 2015 to one of the 15 medical offices and three hospital centers involved in the study. The survey includes the description of the patients (age, sex, practice, skill level, and helmet use), the crash (type, location, estimated speed, causes, and fall description), and the injuries sustained (symptoms, head trauma scores, and other injuries). Sketches were used to describe the crash and impact locations. Clustering methods were used to distinguish profiles of injured participants. **Results**: A total of 295 skiers and 71 snowboarders were interviewed. The most frequent type of mechanism was falls (54%), followed by collision between users (18%) and jumps (15%). Collision with obstacle (13%) caused the most serious TBI. Three categories of patients were identified. First, men age 16–25 yr are more involved in crash at high speed or in connection with a jump. Second, women, children (<16 yr), and beginners are particularly injured in collisions between users. Third, those older than 50 yr, usually nonhelmeted, are frequently involved in falls. Ten crash scenarios were identified. Falling head first is the most frequent of skiers' falls (28%). **Conclusion**: Crash scenarios leading to TBI were identified and associated with profiles of injured participants. Those results should help to better target TBI prevention and protection campaigns. **Key Words:** SKI, SNOWBOARD, HEAD INJURY, CONCUSSION, HELMET

Each year, there are approximately 4500 traumatic brain injuries (TBI) on French ski slopes (1). This type of injury can have dramatic consequences (motor, visual, and behavioral disorders), and it is the leading cause of death among practitioners of winter sports (19,33). The majority of studies on head injuries in skiers and snowboarders have focused on evaluation of the helmet effectiveness. According to these studies, wearing a helmet can reduce the risk of TBI by 15% to 60% (5,12,21,30,35).

For continued improvement in head injury protection for skiers and snowboarders, ski helmets should be developed and evaluated with regard to the reality of the impacts undergone during the crash. For that, it is necessary to identify the circumstances and the mechanisms associated with TBI in skiers and snowboarders. Four main groups of injury mechanisms have been identified in the literature: fall, jump, collision between users, and collision with an obstacle. Fall is the primary cause of TBI for skiers and snowboarders, followed by collision between users and collision with an obstacle (7,11,13,17,24,33). However, few studies have been conducted on the cause, mechanism, and direction of the fall and on the impact location on the head (17,24,25). Such data are needed to understand the kinematics of the crash and head trauma conditions. This has already proved valuable to evaluate means of prevention (2,26,31).

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It has been shown that some characteristics of the injured populations might affect both the behavior on the slope (29) and the severity of the injury (10). In 2010, Ruedl et al. (29) showed that some populations (men, young, and advanced skill level) are more likely to take risks. The same year, Goulet et al. (10) showed that the injury pattern might differ depending on the skill level of the participant. The combination of these two studies suggests that the injury mechanism is linked to the characteristics of the injured populations (age group, type of practice, sex, and skill level). We argue that the description of such a link would allow to better target injury prevention.

In this study, we combine crash analysis and medical survey, thus providing useful information regarding head injury prevention and protection. Our first objective is to identify groups of injured participants based on their injury mechanism (type of mechanism and estimated speed). Our second objective is to describe the cause, the kinematic, and the impact location of each type of crash leading to TBI.

METHODOLOGY

An anonymous questionnaire was constructed and distributed to 15 medical offices in French ski resorts participating in the epidemiological network "Médecins de Montagne" and in the emergency and neurosurgery departments of three hospitals (Annecy, Grenoble, and Marseille). During the 2013–2014 and the 2014–2015 ski seasons, all patients having sustained a clinically diagnosed TBI while skiing or snowboarding were requested to participate in the study. The consent to use information gathered was implied by completion of questionnaire. For the study, TBI included concussions, severe TBI, and skull fractures but excluded lacerations, bruises, and face trauma. The study was approved by the French advisory committee on the treatment of confidential information regarding health care research (Comité consultatif sur le traitement de l'information en matière de recherche dans le domaine de la santé).

The questionnaire consisted of two parts. The first part was filled in by the patient when conscious, or by a witness to the crash. It characterized the patient: age, gender, use of helmet, type of practice (ski or snowboard), and skill level (beginner, intermediate, or advanced). It described the crash: mechanism (fall, collision with users, collision with obstacle, and jump), cause (too high speed, handling errors, lack of attention, and poor visibility or jump), location (off-trail, terrain park, ski-lift, easy, and medium or hard slope), estimated speed (null, low–medium, high, or too high), and, via sketches, accurately located the affected areas of the head. It was completed by a choice among 18 sketches illustrating specific crash scenarios (6 sketches for skier falls, 4 sketches for snowboarder falls, 2 sketches for jumps, and 3 sketches for collisions between users and 3 sketches for collisions with an obstacle). The creation of these sketches was supported by the analysis of crash scenarios from approximately 100 videos selected online using the following keywords: "ski," "snowboard," "accident," "crash," and "head injury." The second part was filled in by the physician when the patient arrived in the medical facility. It included information on the patient's state of consciousness (Glasgow score and neurological signs) and associated head, neck, and face injuries. The injuries that the injured participant might have sustained in other body parts were not recorded. All sketches and the details of the categories can be found in the questionnaire, available as a supplemental digital content (see document, Supplemental Digital Content 1, anonymous survey on TBI, http://links.lww.com/MSS/A741).

In the 15 medical centers, when a TBI was suspected, injured people were requested by the secretary of the facility to participate in the study. If they accepted, they were asked to complete the first part of the questionnaire before seeing the physician and were provided with documentation on the study and on the questionnaire. The physician's role was to verify briefly the information provided by the injured person and to complete the medical part. To ensure the questionnaire was filled consistently in the 18 medical facilities, the physicians who participated in the study were briefed beforehand.

The injury mechanisms were grouped into the four categories previously mentioned, namely, falls, jumps, collisions between users, and collisions with obstacles. During the analysis, we verified that the chosen mechanism was consistent with the selected sketch: in case of mismatch, the questionnaire was not included in the study. Also when two mechanisms were selected by the patient (e.g., fall and collision with user), collisions and jump were selected over the fall as the information regarding the fall was found in the selected sketches (e.g., sketch "self-fall followed by collision"). On the contrary, multiple answers were possible for two questions: the question regarding the cause of the crash and the question regarding the location of the head impact, for instance, a fall can lead to multiple impacts. All the answers provided for these two questions were included in the analysis. For the analysis, four age groups homogeneous in size were defined : >16, 16–25, 25–50, >50 yr. Also, because of the small number of beginners, two groups of skill levels were defined: beginner and intermediate grouped under the term "less skilled" and advanced under the term "more skilled." In addition, we grouped the estimated speed "zero" and "low to medium" under the term "low" and the estimated speed "high" and "too high" under the term "high." TBI severity was ranked according to the Head Injury Severity Scale (34): minimal (Glasgow Coma Scale [GCS] = 15, no loss of consciousness [LOC]), mild (GCS = 14 or GCS = 15 and LOC), moderate (GCS = 9–13 or LOC > 5 min), serious (GCS < 8).

Analysis of the results was conducted in three stages. First, the characteristics of patients and the severity of the TBI were compared for each type of injury mechanism using a one-way ANOVA. Missing data were not included in the analysis, and two-tailed P values <0.05 were used for statistical significance. Second, categories of injured participants were identified using a multiple component analysis (MCA) followed by an ascending hierarchical classification (AHC) using Ward's method ($P < 0.05$). The MCA was performed on the variables "skill level," "estimated speed," "age," "sex," and "injury mechanism," on patients who lacked none of these variables, i.e., 279 individuals. The variable "helmet use" was not included in the MCA because it was highly correlated with the variable "age," which hid the other relationships between variables. Finally, for the most selected sketches, the characteristics of the crash and the impact areas were compared. The statistical analyses were performed using Statistica 11 and R software.

RESULTS

Profile of the Injured and Injury Mechanism

During the seasons 2013–14 and 2014–15, 316 questionnaires were completed in the 15 medical offices, and 50 questionnaires were completed in the three hospital centers of Marseille, Grenoble, and Annecy. Table 1 presents the characteristics of the patients included in the study. These were mainly men (60%), who were skiing (80%), who were wearing a helmet (60%), and who described their skill level as intermediate (44%). The great majority of TBI recorded (89%) were minimal or mild (Glasgow score >13), and 6% were considered moderate or serious (Glasgow score <14). The primary injury mechanism of head injury was falls (54%), followed by a collision between users (18%), jumps (15%), and collision with an obstacle (13%). The collision with an obstacle, however, was the mechanism associated with the highest severity: 48% of the TBI diagnosed as moderate or serious occurred during a collision with an obstacle. Regarding neurological signs, 42% of the injured included in the study had an initial LOC, 19% were disoriented during their medical examination, and 7% had visual disturbances.

Figure 1 shows the MCA and the results of the AHC based on the variables "skill level," "estimated speed," "age," "sex," and "injury mechanism." The classification reveals three profiles of the injured ($P < 0.05$) (Fig. 1). The first group (group 1) contains young men with an advanced level. This group is associated with high speed during the crash and the injury mechanism "jump." The second group (group 2) includes women and children (<16 yr) and is associated with a beginner and intermediate level and the "collision with user." Finally, the third group (group 3) consists mainly of people older than 50 yr and is characterized by the "fall" as injury mechanism and an advanced level of practice. The latter two groups are associated with a low speed during the crash.

The features "collisions with obstacles" and "26–50 yr" are not significantly differentiated in this classification.

Helmet use was highly dependent of the participant's age. In fact, the vast majority of those younger than 25 yr wore a helmet (90% and 63% for those <15 and 15–25 yr, respectively), whereas only 46% of those older than 25 yr wore helmets. Hence, more of those in groups 1 and 2 (Fig. 1) wore helmets (62% and 63%, respectively) than in group 3 (51%). In addition, the majority of those with high severity TBI (moderate or serious) belonged to group 1 (56%).

Detailed Description of the Crash

Fall: the most frequent injury mechanism. Falling is the most frequent injury mechanism for skiers (53%) and snowboarders (56%). The detailed characteristics of these

TABLE 1. Characteristics of the injured participants.

		Total	Fall	Collision User	Collision Obstacle	Jump	ANOVA
		n (% total)	*n* (% raw)	*n* (% raw)	*n* (% raw)	*n* (% raw)	*P*
Total		**366**	**196 (54)**	**65 (18)**	**49 (13)**	**56 (15)**	
Practice	Ski	**295 (80)**	156 (53)	55 (19)	45 (15)	39 (13)	0.02
	Snowboard	**71 (20)**	40 (56)	10 (14)	4 (6)	17 (24)	
Sex	Female	**145 (40)**	77 (53)	41 (28)	16 (11)	11 (8)	>0.001
	Male	**221 (60)**	119 (54)	24 (11)	33 (15)	45 (20)	
Age (yr)	<16	**83 (23)**	36 (43)	19 (23)	12 (14)	16 (19)	0.45
	16–25	**86 (23)**	50 (58)	13 (15)	8 (9)	15 (17)	
	26–50	**116 (32)**	57 (49)	23 (20)	19 (16)	17 (15)	
	>50	**62 (17)**	43 (69)	9 (15)	7 (11)	3 (5)	
	MD	**19 (5)**	10 (50)	1 (5)	3 (15)	5 (25)	
Skill level	Beginner	**41 (11)**	23 (56)	7 (17)	10 (24)	1 (2)	0.17
	Intermediate	**163 (44)**	84 (52)	34 (21)	17 (10)	28 (17)	
	Advanced	**127 (35)**	68 (53)	18 (14)	17 (13)	24 (19)	
	MD	**35 (10)**	21 (60)	6 (17)	5 (14)	3 (9)	
Helmet use	Yes	**219 (60)**	123 (56)	40 (18)	18 (8)	38 (17)	0.13
	No	**138 (38)**	69 (50)	23 (17)	30 (22)	16 (12)	
	MD	**9 (2)**	4 (44)	2 (22)	1 (11)	2 (22)	
TBI severity	Minimal	**160 (44)**	93 (57)	28 (18)	14 (9)	25 (16)	0.17
	Mild	**165 (45)**	85 (52)	32 (19)	22 (13)	26 (16)	
	Moderate	**18 (5)**	5 (28)	1 (5)	9 (50)	3 (17)	
	Serious	**5 (1)**	1 (20)	2 (40)	2 (40)	0 (0)	
	MD	**18 (5)**	11 (61)	3 (17)	2 (11)	2 (11)	
Other injury							
Head	Fracture	**12 (3)**	1 (2)	5 (10)	6 (3)	0 (0)	
	Other	**140 (38)**	20 (30)	28 (57)	63 (32)	29 (52)	
Face	Fracture	**19 (5)**	3 (5)	4 (8)	11 (6)	1 (2)	
	Dental trauma	**13 (4)**	4 (6)	2 (4)	6 (3)	1 (2)	
	Other	**90 (25)**	15 (23)	17 (35)	43 (22)	15 (27)	
Neck	Fracture	**7 (2)**	0 (0)	1 (2)	5 (3)	1 (2)	
	Whiplash	**31 (8)**	5 (8)	1 (2)	20 (10)	5 (9)	

MD, missing data. Numbers in bold indicate total.

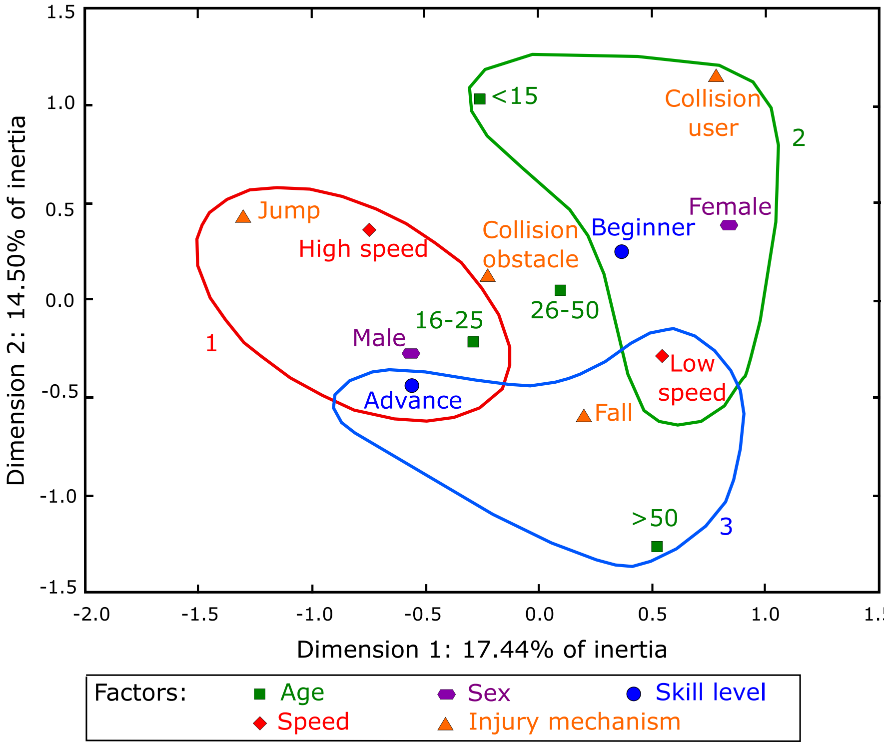

FIGURE 1—MCA based on five variables: "skill level," "estimated speed," "age," "sex," and "injury mechanism." The circled group are differentiated based on an AHC (*P* < 0.05).

falls are presented in Table 2 and Figure 2. "Falling head first" while skiing was the most frequently selected sketch (28% of skiers' falls and 12% of all the crash), but it was only related to minimal or mild TBI. However, these TBI were often associated with other trauma: cervical (seven sprains and five fractures), facial (three fractures and two dental traumas), or skull (two fractures). "Falling sideways (catching the ski edge)," representing 19%, was the second most frequent type of skiers' falls. The recorded falls were mainly forward, which explains why the two principal affected areas were the frontal and facial areas (Table 2).

Regarding the snowboarder, the two types of falls identified were falling "forward" (38%) and falling "backward" (41%), particularly cited by beginners (44%).

Finally, whether for skiers or snowboarders, falling occurred at fairly low speeds (52%), and its main cause was "handling error" (32%). The falls occurred primarily on easy slopes (37% and 64% for skiers and snowboarders, respectively) and were often followed by rolling and long slides.

Collision between users: women, children, and beginners particularly affected. The collision between users was involved in 18% of the TBI recorded. As shown by the MCA (Fig. 1), it particularly affected children, women, and people with a lower skill level. In 62% of cases, the collision between users involved an "impacting" user moving at high speed before the collision and an "impacted" user who was stationary or moving at low speed (Table 3). In 55% of cases, the injured participant was the "impacted" user. These collisions occurred mainly on easy slopes (55%) and were caused by excessive speed in 32% of cases. During a collision with another user, the frontal, occipital, and facial areas were frequently affected (in 36%, 35%, and 33% of cases, respectively) (Table 3), and 5% of these collisions led to high severity TBI (moderate or serious).

Collision with an obstacle: the most severe injury mechanisms. Forty-eight percent of high severity TBI (GCS < 13) were caused by a collision with an obstacle (tree, rocks, lift pole, etc.). Among the 49 collisions recorded, 8 were against a tree, 8 were against a pylon or electricity pole, 7 were against a rock or a rigid wall, 4 were against an ice wall, and 3 were against a ski-lift pole. The information regarding the other collisions was not available. In 70% of cases, the collision was the result of a prior fall by the user (Table 3). As with falling, "handling error" was most often given as the cause of collision (29%). "Too high speed" was also often mentioned (18%). The majority of collisions with obstacles occurred on the easy and medium difficulty slopes (29% and 33%, respectively), but unlike the previous types of injury mechanisms, some collisions also occurred off-trail (14%). The face was the area most affected in a collision with an obstacle (43%): 11 facial fractures and 6 dental traumas were caused by this type of collision.

Another major difference; only 37% of patients involved in collision with obstacle were wearing a helmet, compared with 63% for falling, 62% for the collision between users, and 68% for jumping.

Jump: the injury mechanism of the advanced level young man. TBI caused by jumps particularly

TABLE 2. Detailed description of the skier and snowboarder fall.

Injury Mechanism	Skier Fall, *n* = 156 (43% of all crashes)					Snowboarder Fall, *n* = 39 (11%)		
Scenario Description	Falling Head First	Falling Sideways (Edge Catching)	Crossing Skis	Falling Backward (Imbalance)		Falling Head First	Falling Backward	
Scenario Sketch	Figure 2A	Figure 2B	Figure 2C	Figure 2D	Others[a]	Figure 2I	Figure 3J	Others[b]
Total, *n* (% raw by injury mechanism)	44 (28)	29 (19)	18 (12)	22 (14)	43 (28)	15 (38)	16 (41)	8 (21)
Location, *n* (% column)								
Blue slope (easy)	**23 (52)**	10 (34)	**11 (61)**	**9 (41)**	16 (37)	**9 (60)**	**10 (63)**	6 (75)
Red slope (medium)	15 (34)	**15 (52)**	2 (11)	**10 (45)**	14 (33)	2 (13)	3 (19)	0 (0)
Black slope (hard)	0 (0)	3 (10)	3 (17)	1 (5)	3 (7)	1 (7)	0 (0)	0 (0)
Others/MD	6 (14)	1 (3)	2 (11)	2 (9)	10 (23)	3 (20)	3 (19)	2 (25)
Cause, *n* (% column)								
Too high speed	6 (13)	4 (1)	2 (11)	5 (9)	8 (19)	2 (12)	3 (19)	0 (0)
Handling errors	**13 (25)**	**16 (52)**	**8 (44)**	**6 (26)**	13 (30)	**9 (53)**	**9 (56)**	5 (56)
Lack of attention	6 (13)	4 (13)	5 (28)	4 (17)	5 (11)	0 (0)	1 (6)	1 (11)
Poor visibility	**11 (24)**	1 (3)	1 (6)	2 (9)	2 (5)	2 (12)	1 (6)	0 (0)
Other	10 (22)	6 (19)	2 (11)	9 (39)	16 (36)	4 (24)	2 (13)	3 (33)
Speed, *n* (% column)								
Low	**26 (59)**	**14 (48)**	**8 (44)**	**13 (59)**	21 (49)	**11 (73)**	**10 (63)**	7 (88)
High	15 (34)	**14 (48)**	**7 (39)**	6 (27)	12 (28)	3 (20)	3 (19)	0 (0)
MD	3 (7)	1 (3)	3 (17)	3 (14)	10 (23)	1 (7)	3 (19)	1 (13)
Additional description, *n* (% column)								
Binding release	**17 (39)**	**12 (41)**	4 (22)	**8 (36)**	11 (26)	0 (0)	0 (0)	0 (0)
User rolled	**14 (32)**	6 (21)	4 (22)	3 (14)	9 (21)	**6 (40)**	2 (13)	1 (13)
Long slide	7 (16)	4 (14)	1 (6)	0 (0)	6 (14)	2 (13)	**5 (31)**	2 (25)
Affected area, *n* (% column)								
Frontal	**25 (57)**	**9 (31)**	6 (33)	3 (14)	**14 (33)**	**7 (47)**	3 (19)	1 (13)
Facial	**18 (41)**	7 (24)	5 (28)	5 (23)	7 (16)	**7 (47)**	6 (38)	0 (0)
Parietal	8 (18)	2 (7)	1 (6)	3 (14)	4 (9)	0 (0)	1 (6)	1 (13)
Temporal	2 (5)	0 (0)	0 (0)	1 (5)	3 (7)	1 (7)	0 (0)	2 (25)
Occipital	10 (23)	**8 (28)**	**9 (50)**	**16 (73)**	7 (16)	0 (0)	**9 (56)**	1 (13)

[a]Six (3%) spreading skis, 5 (3%) the inner edge of the ski is blocked in the snow, and 32 (19%) missing data (MD).
[b]One (2%) in the front tip of the snowboard direction, 1 (2%) in the back tip of the snowboard direction, and 6 (15%) missing data. Numbers in bold indicate higher numbers.

affected the population of advanced level young men (Fig. 1) and helmeted (68%). Most of the patients involved in jumps reported moving at high speed before the crash (61%), unlike those involved in falls and collisions between users (31%). The other characteristic of the jumps is their location because 48% of head injuries related to jumping took place within the terrain park. Although 59% of jumps led to a forward fall, it was the occipital area, which was most affected during a fall (in 38% of falls) (Table 3).

DISCUSSION

The detailed study of skiing and snowboarding crash circumstances and injury mechanisms involved in TBI has

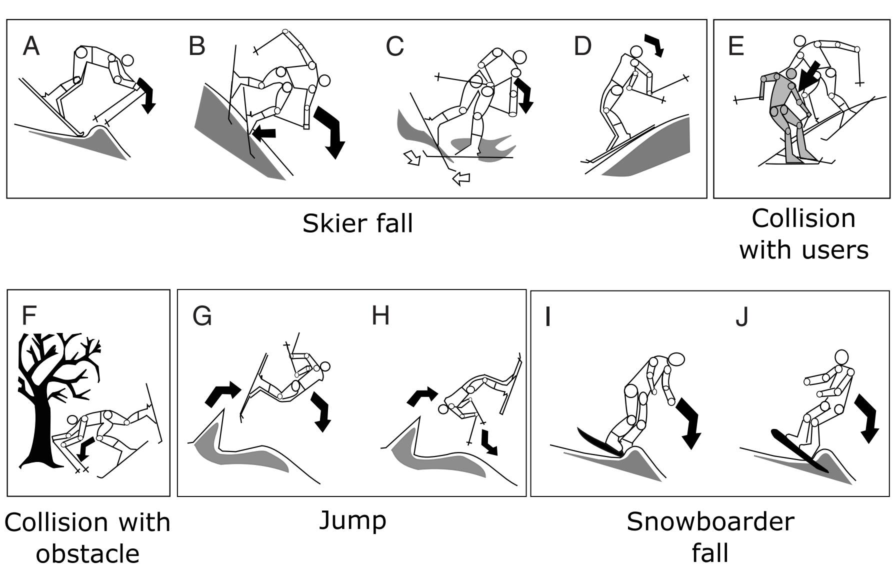

FIGURE 2—The 10 most selected scenarios: falling head first (*n* = 44) (A); falling sideways (edge catching) (*n* = 29) (B); crossing skis (*n* = 18) (C); falling backward (imbalance) (*n* = 22) (D); user collides with another immobile or less rapid user (*n* = 41) (E); self-fall, followed by a collision with obstacle (*n* = 35) (F); jump forward (*n* = 33) (G); jump backward (*n* = 23) (H); snowboarder falling head first (*n* = 15) (I); and snowboarder falling backward (*n* = 16) (J).

TABLE 3. Detailed description of collisions and jumps.

Injury Mechanism	**Collision between Users, *n* = 66 (18% of all Crashes)**		**Collision with Obstacle, *n* = 49 (13%)**		**Jump, *n* = 56 (15%)**	
Scenario Description	**User Collides with Another Immobile or Less Rapid User**		**Self-fall, Followed by a Collision with Obstacle**		**Forward**	**Backward**
Scenario Sketch	**Figure 2E**	**Other[a]**	**Figure 2F**	**Other[b] (Direct Collision)**	**Figure 2G**	**Figure 2H**
Total, *n* (% raw by injury mechanism)	41 (62)	25 (38)	35 (69)	15 (31)	33 (59)	23 (41)
Location, *n* (% column)						
Blue slope (easy)	**22 (54)**	14 (56)	**11 (32)**	3 (20)	4 (12)	1 (4)
Red slope (medium)	**17 (41)**	7 (28)	**13 (38)**	3 (20)	6 (18)	4 (17)
Terrain park	0 (0)	0 (0)	0 (0)	0 (0)	**15 (45)**	**12 (52)**
Off-trail	0 (0)	0 (0)	3 (9)	4 (27)	4 (12)	3 (13)
Ski-lift	0 (0)	0 (0)	1 (3)	4 (27)	0 (0)	0 (0)
Other/MD	1 (2)	0 (0)	6 (18)	1 (7)	4 (12)	3 (13)
Cause, *n* (% column)						
Too high speed	**14 (33)**	7 (26)	6 (16)	4 (25)	7 (19)	5 (22)
Handling errors	4 (9)	6 (22)	**13 (35)**	1 (6)	3 (8)	4 (17)
Lack of attention	4 (12)	2 (7)	5 (14)	3 (19)	2 (5)	0 (0)
Poor visibility	3 (7)	2 (7)	3 (8)	2 (13)	2 (5)	1 (4)
Jumping	2 (5)	0 (0)	(0)	0 (0)	**22 (59)**	**13 (57)**
Other	15 (35)	10 (37)	10 (27)	6 (38)	1 (3)	0 (0)
Speed, *n* (% column)						
Low	**25 (61)**	10 (40)	15 (44)	9 (60)	9 (27)	11 (48)
High	14 (34)	8 (32)	**16 (47)**	5 (33)	**22 (67)**	**12 (52)**
MD	2 (5)	7 (28)	3 (9)	1 (7)	2 (6)	0 (0)
Additional description, *n* (% column)						
Binding release	9 (22)	8 (32)	7 (21)	2 (13)	16 (48)	5 (22)
User rolled	10 (24)	6 (24)	4 (12)	1 (7)	11 (33)	7 (30)
Long slide	7 (17)	1 (4)	3 (9)	1 (7)	6 (18)	1 (4)
Affected area, *n* (% column)						
Frontal	**14 (34)**	10 (40)	10 (29)	6 (40)	**14 (42)**	3 (13)
Facial	**13 (32)**	9 (36)	**13 (38)**	8 (53)	12 (36)	5 (22)
Parietal	4 (10)	2 (8)	7 (21)	1 (7)	6 (18)	0 (0)
Temporal	2 (5)	1 (4)	1 (3)	1 (7)	0 (0)	0 (0)
Occipital	**15 (37)**	8 (32)	**13 (38)**	3 (20)	3 (9)	**21 (91)**

[a]Ten (15%) face-to-face collision (frontal or side impact), 8 (12%) the wound is caused by a fall against snow induced by a collision, and 7 (11%) missing data (MD).
[b]Eleven (22%) direct impact of all the body with the obstacle, 3 (6%) only the head impact the object, and 1 (2%) missing data. Numbers in bold indicate higher numbers.

allowed us to highlight three categories of injured participants and to precisely identify 10 specific crash scenarios. These results provide access to accurate knowledge of head impact conditions during a crash. This knowledge is needed to better design and evaluate protections. Results also provide key information to better target head injury prevention campaigns on the ski slopes.

Injured Population Groups and Implications for Prevention Strategies

Injured population. The results of the MCA and of the classification highlighted three groups of injured participants (Fig. 1).

The first group (group 1, Fig. 1) is mainly composed of young men (15–25 yr) with an advanced skill level. They were mainly injured during jumps or in high-speed crashes. This was expected as it had already been identified that advanced level young men engage in high speed and risky behavior on the slopes: Ruedl et al. (29) showed that the young, men, and advanced practitioners considered themselves to be risk takers, that they traveled at a higher speed than the other users on the slopes (27), and that they were more likely to injure themselves in the terrain park (28). It had also been shown that young men have an increased risk of head injury (18,35). Our study confirms that risky behaviors already identified on the slopes were found in the types of crash experienced by this group of participants. This study also showed that the most severe TBI belong to this group of practitioners (56% of the moderate and serious TBI). This is consistent with the work of Goulet et al. (9), showing that crashes involving advanced practitioners or taking place in terrain parks were more likely to cause serious injury. The majority recorded in this group in our study wore a helmet (63%), which is consistent with Sulheim et al. (35).

Individuals in the other two groups were involved in crashes at low or medium speed, suggesting lower risk taking.

The second group (group 2, Fig. 1) consists mainly of women, children, and beginners. These individuals are particularly involved in collisions between users. Children had already been identified as being particularly involved in collisions between individuals (1) because of their small size, making them less visible and more vulnerable to head impacts (blows from the elbow, shoulder, or stakes). In our study, the great majority of children were helmeted (90%). This is consistent with the rate of helmet use among children observed in French ski slopes: according to the Association "Médecins de montagne," 97% of children were wearing helmets on French slopes in 2012 (1).

The third category (group 3, Fig. 1) is primarily composed of individuals older than 50 yr with an advanced level who were mainly involved in falls. To our knowledge, little work has been conducted on older skiers; however, impaired balance, fatigue, and loss of flexibility (arthritis) make them a population at risk (15). Among the seniors in our study, relatively few wore helmets (45%).

Injury prevention strategies. The identification of these three groups of practitioners with different types of risk behaviors allows better targeting of prevention measures. First, the message about the danger of so-called risky behaviors such as jumps and high speed should primarily target young men and terrain park areas. Second, we showed that 62% of collisions between users leading to TBI happened on easy slopes. Those slopes are used by skiers of all skill levels (from beginner to advanced), but it was mostly beginner skiers who were involved in collisions. Possible causes of this result are the high density of skiers on easy slopes and the great difference in speed between the participants on those slopes (4,32). This might particularly affect beginners because of their difficulty to control their trajectory. If those causes are verified, several methods could be considered to reduce the number of collisions on easy slopes: we may for instance restrict some slopes to beginners to reduce the density and the speed. This suggestion is consistent with the work of Lystad (20) and Bergstrøm and Ekeland (3). Third, we showed that children were the primary victims of collisions. Reducing the risk of TBI could be achieved by educating children on safe behavior on slopes and by making other users more aware of the presence of children. Finally, only few injured seniors wore a helmet during the crash. To reduce their risk of TBI, incentive campaigns, previously focused on children, could be expanded to include seniors.

Detailed Descriptions of Injury Mechanisms

General description. The results of the study showed that the most frequent injury mechanisms leading to TBI are falls (54%), followed by the collision between users (18%) and jumps (15%). The collision with an obstacle only represented 13% but caused the most serious TBI.

Most studies agree that the mechanisms most frequently involved in TBI are falls, and that the most severe mechanisms are collisions with obstacles (18). According to the study of Nakaguchi et al. (24) of 314 patients treated at the Suwa hospital (Japan), 50% of TBI are caused by falls, 27% by collisions (with an object or between users), and 15% by jumps. These trends are confirmed by the results of Greve et al. (11), based on 1135 skiers and snowboarders admitted to nine "medical facilities" in the United States, showing falls and jumps were involved in 74% of TBI, compared with 10% and 13% for collision between users and collision with an obstacle, respectively. Regarding the most serious mechanisms, Xiang and Stallones (36) showed that more than 60% of deaths associated with skiing and occurring between 1980 and 2001 in Colorado involved a collision with obstacles. For snowboarders, jumping is the second most important mechanism (20% of TBI), which is consistent with the results of Koyama et al. (17), showing that jumping was involved in 34% of TBI in 2367 snowboarders with TBI treated at the Saito Hospital (Japan). The slight discrepancies between studies may be explained by the fact that the injury mechanism affects the severity of injuries, and that the severity of the TBI in each study depends on the nature of the data collection.

Moreover, we noticed a low representation of snowboarders among our sample (19%). This is logical because according to the Association "Médecins de Montagne," they represented only 16% of snow sport practitioners on French slopes in 2012.

Falls. The results of our study showed that the snowboarder falling direction associated with TBI is mostly in the frontal plane and is distributed evenly between the front and rear (38% and 41%) (Table 2). In 2002, Nakaguchi and Tsutsumi (25) associated this type of fall with a mechanism termed "opposite-edge phenomenon," described as the edge of the snowboard catching in the snow in a direction opposite to the direction of the turn, causing a sudden stop and the projection of the snowboarder's upper body against the slope. The "opposite-edge phenomenon" in the study of Nakagushi et Tsutsumi, as in ours, primarily involved beginners and intermediates.

Regarding the skier, only the general direction of the fall associated with TBI had previously been studied: it was primarily toward the front (54%) (24). The results of our study confirmed this finding and clarified the kinematics of these falls. "Falling head first" and "crossing skis" represented 40% of falls and clearly imply a forward fall. This preferred forward direction explains why the frontal and facial areas were the most affected during a skier's fall (34% and 25%, respectively). Regarding other fall directions, two scenarios were identified: "falling sideways" involving an edge fault (19%) and rear imbalance (14%).

Collisions. The results of the study showed that collisions with an obstacle were mostly the result of a fall. The collision may be preceded by a slide. The initial fall and sliding before the collision considerably influenced the kinematics and the severity of the crash. This information is therefore essential and should be taken into account during a crash reconstruction to obtain realistic head impact conditions. Also, in these specific circumstances we cannot assess whether the impact of the head leading to the TBI occurred against the snow during the initial fall or against the obstacle during the collision.

Our study also showed that the great majority of collisions between users involved an "impacting" user moving at high speed before the collision and an "impacted" user who was stationary or moving at low speed. This information may influence prevention campaigns in two ways. First, it emphasizes the importance of ensuring that one can be seen by other users when stopping on the slopes (not behind a mogul, for example). Second, it confirms the importance of wearing a ski helmet, even when one is considered a careful skier. In fact, in 55% of cases, it was the affected user who sustained the TBI.

Implications for the Helmet

The energy absorption capacity of the helmet is dependent on the speed of impact and the affected area (6). Therefore, to better prevent TBI, protection must be designed and tested under realistic impact conditions (22). This study allowed us to refine the knowledge of these impact conditions.

First, at least 68% of TBI took place during a head impact with the snow (falls and jumps). At present, helmets are tested against a rigid surface, whose mechanical properties can be very different from that of snow: helmet efficacy against snow should therefore be studied.

Second, the frontal and occipital areas were the most affected areas (Tables 2 and 3). These areas should be consequently protected as a priority. The facial area, not protected by most current helmets, was also affected in 24% of cases. This argues for the study of full-face helmets on the ski slopes.

Third, the detailed description of the crash scenarios frequently involved in TBI opens new possibilities for crash reconstruction. For instance, the identification of the snowboarders' typical injury mechanism, the "opposite-edge phenomenon," and then its experimental reproduction by Scher et al. and later by Bailly et al. enabled the evaluation of head impact conditions during the crash and evaluation of the helmet under these conditions (2,25,26,31). Our study, by presenting accurate injury mechanisms of snowboarder and skier, provides access to realistic head impact conditions during the crash most frequently involved in TBI.

Limitations

The originality of this work was to present scenarios of crash in the form of sketches to describe the crash in the most detailed way. To comprehensively define these sketches, many crash videos were viewed, and the sketches were validated by physicians and mountain rescuers. However, it is possible that some scenarios were neglected.

Special attention was paid to the representativeness of our sample. The target for the sample size was calculated from the estimated number of TBI on French slopes made by the association "Médecins de Montagne": 3% of the 150,000 injured, i.e., 4500 TBI per year on French slopes. To have information representative of this population with a 95% confidence level (±5% accuracy level), the necessary sample size was 368 individuals $\left(n = \frac{4500}{1+4500*5\%} = 368\right)$. After 2 yr of study, our sample ($n = 366$) almost reached this goal.

In addition, the vast majority of TBI related to skiing and snowboarding are treated by ski resort physicians in France. However, those with the most serious TBI are usually transferred directly to the nearest hospitals and "bypass" the ski resort physicians. Among the 366 injured recorded in our database, the ratio of those injured coming from ski resort medical offices and from hospitals may not be representative. That could affect the level of severity of our entire database. In addition, for ethical reasons, we did not collect information regarding the injured people who refused to participate in the study. We were hence not able to control the potential selection bias associated with the choice to participate.

The study was conducted in 18 facilities, and many physicians were responsible for the quality of the data and for the evaluation of the severity of the TBI. The level of agreement between the physicians was not measured. However, to ensure the homogeneity of answers, they were briefed beforehand. We also chose to evaluate the severity of the TBI based on the Glasgow score (GCS), which is well known and commonly used by all the physicians participating to the study. Two factors might have biased the GCS. First, the interrater variability between the physicians: according to literature, the level of interrater agreement for GCS is moderate to high (8,14,23). Second, the variation in transport time between the resort and the medical offices and hospitals might affect patient's condition and hence the severity score (16).

The study provided information regarding the estimation of the speed of the participant before the crash. This information can be very useful as the energy involved during the crash is closely linked with the kinetic energy of the participant before the crash. However, this information has to be considered carefully as it has been shown that the perception of skiing speed might depend on various factors such as sex, skill level, and risk taking behavior (4,32).

Finally, concerning the quality of the responses to the questionnaires, two elements require clarification. First, patients had suffered from a TBI, sometimes associated with memory impairment, which might affect the quality of the responses. Second, the part of the questionnaire concerning the description of the crash had to be filled in either by the patient when capable, or by a witness to the crash, when the patient was either unconscious or disoriented. According to the physicians participating to the study, the survey was most of the time filled in by the patient (only 6% sustained a moderate or serious TBI); however, we do not know the exact number of questionnaires filled in by witnesses. This difference in perspective may have affected the estimation of speed and of the cause of the crash. Indeed, injured people's perception of their own behavior might differ from that of the witness. For instance, the witness might perceive a risky behavior (i.e., too fast), whereas the injured person might have felt in control of its speed. However, this difference should not have biased the answers to questions not open to interpretation such as patient information, injury mechanism, and crash location.

CONCLUSION

This study, combining epidemiological data and the analysis of injury mechanisms, is the first to accurately identify skiing and snowboarding injury mechanisms regularly involved in head injuries. The majority of these injury mechanisms were falls, with a traumatic impact between the head and the snow. However, the most serious crashes resulted from a collision with an obstacle.

Ten scenarios of snow sport crashes were identified and examined in detail. In particular, we have shown that "falling head first" is the most frequent scenario (12% of crashes). It was also demonstrated that the collision with an obstacle was usually secondary to a fall, whereas the collision between users typically involved an "impacting" skier moving at high speed and an "impacted" individual stopped or moving at low speed. The detailed description of these different crashes opens new possibilities in crashes reconstruction, allowing access to specific head impact conditions—necessary data for the evaluation and improvement of ski helmets.

The study also identified three categories of those injured. First, young men are more involved in crashes at high speed or in connection with a jump. Next, women, children, and beginners are particularly injured in collisions between users. Finally, seniors are more likely to be involved in falls. These results should help to better target head injury prevention campaigns on the ski slopes.

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