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Recent Trends in Ski-related Injuries

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Abstract: In skiing, a strong correlation has long existed between injuries and the development of ski equipment. For instance, just one change in the shape of skis leads to changes in skiing style, which can make the skier adopt knee positions likely to create injury. In this review, we discuss the morphology of ski-related injuries. In the 18 years since 1996, 10,561 patients with skiing and snowboarding-related injuries visited the Ishiuchi Ski Clinic (Niigata Prefecture, Japan). Of these, 3,703 patients had ski-related injuries. We reviewed patients' medical records and questionnaires and observed their skiing using a video camera with 3-dimensional computer graphics software analysis. When knee sprains and fractures were considered together, the 18-year overall incidence was 30%, but in the 3-year period from 2009–2012, the incidence increased to 31%. Skiing style has changed from conventional alpine skiing to carving skiing, which has made the knee unstable, thereby increasing the risk of anterior cruciate ligament injury or tibial plateau fracture.

Key words: ski, snowboard, carving skiing, ACL, tibial plateau

Introduction

In skiing, a strong correlation between injuries and the development of ski equipment has been evident for a long time[1–5)]. For instance, a change in the shape of the skis can lead to changes in the skiing style, which may make skiers adopt knees positions that are more likely to result in injury. Since the advent of carving skis in 1999, there has been much debate on how this change would theoretically increase knee injuries[6–19)]. However, there have been no evaluations or reports based on scientific evidence on (i) the changes in injury statistics or (ii) the specific mechanism underlying knee injuries to validate these theories.

Based on our statistics of ski-related injuries collected over an 18-year period, we hereby report on the morphology of ski-related injuries with a brief review of the literature.

Subjects and methods

In the 18 years since December 1996 (18 winter seasons: December 1996–March 2014), 10,561 patients with skiing- and snowboarding-related injuries visited the Ishiuchi Maruyama Ski Clinic

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of the Department of Orthopedic Surgery, Showa University (Niigata Prefecture, Japan). Of these, 3,703 patients had a ski-related injury. We retrospectively reviewed patients' medical records and questionnaires and observed their skiing by a video camera. We then compared these observations with 61,378 earlier patients with a ski-related injury who were treated during the 40-year period after 1957 (40 winter seasons: December 1957–March 1997). Based on this comparison, we examined the following:

1. The mechanism and morphology of ski-related injuries

We examined the medical records of patients who sustained ski- and snowboarding-related injuries over the 18-year period from December 1996 to March 2014 according to the site and type of injury. We identified the characteristics of ski-related injuries that differed from snowboarding-related injuries, in order to investigate the mechanism and morphology of ski-related injuries, focusing on the involvement of falls, collisions, and the development of ski equipment.

2. Changes in ski-related injury statistics

We examined changes in the top 10 ski-related injuries that occurred over the 18-year period from December 1996 to March 2014, especially changes in the order of incidence of the ski-related injuries. Periods of changes in injuries could be broadly divided into the following four time spans: Period 1, the early 6-year period when conventional alpine skis were still popular (December 1996–March 2002); Period 2, the 7-year span covering the earlier middle period when the 2002 and 2006 Winter Olympics were held, and there was a shift in the shape of skis from alpine skiing to carving skiing (December 2002–March 2009); Period 3, the 3-year span covering the later middle period when the 2010 Winter Olympics were held, and carving skis were generally used by skiers in Japan (December 2009–March 2012); and Period 4, the most recent 2-year period (December 2012–March 2014). In particular, we studied changes in the type of injuries, such as knee sprains and fractures.

3. The mechanism underlying injury to the knee

During the four periods mentioned above, we investigated changes in the skiing style using a video camera and 3-dimensional computer graphics analysis software (Smith Micro Software, Inc., Aliso Viejo, CA, USA). We examined whether such changes led to positions whereby the knees were more prone to injury.

Based on the evaluations obtained, we reviewed the characteristics of ski-related injuries and the morphology of recent ski-related injuries that have increased lately with the development in ski equipment.

Results

1. The mechanism and morphology of ski-related injuries

Of the 3,703 patients examined with ski-related injuries over the 18-year study period, the most common injury was to the lower limb (2,127 patients; 57.4%), followed by injury to the

upper limb (865 patients; 23.4%), head and face (382 patients; 10.3%), and trunk (329 patients; 8.9%; Table 1). Injury to the knee was the most common site of injury (1,164 patients; 31.4%), followed by femur (551 patients; 14.9%), head and face (382 patients; 10.3%), ankle (284 patients; 7.7%), and shoulder/blade (253 patients; 6.8%). Sprains, such as ligament injuries, were the most common type of injury (1,369 patients; 37.0%), followed by fractures (1,041 patients; 28.1%), and lacerations and contusions (498 patients; 13.4%). In contrast, 6,858 snowboarding-related injuries occurred during the 18-year study period, and the majority involved upper limb injuries (3,625 patients; 52.9%), followed by injury to the lower limb (1,428 patients; 20.8%), trunk (1,091 patients; 15.9%), and head and face (714 patients; 10.4%; Table 2). For snowboarders, injuries to the wrist were the most common site (1,123 patients; 16.4%), followed by shoulder and shoulder blade (761 patients; 11.1%), lower back and spine (756 patients; 11.0%), head and face (714 patients; 10.4%), and elbow (632 patients; 9.2%). Fractures were the most common type of injury in snowboarders (2,571 patients; 37.5%), followed by sprains, such as ligament injury (1,385 patients; 20.2%), and lacerations and contusions (1,030 patients; 15.0%). In order of incidence, the most common ski-related injuries were knee sprains, such as the medial collateral ligament and anterior cruciate ligament (ACL; 861 patients; 23.3%), followed by laceration and contusion to the head and face (312 patients; 8.4%), fracture of the femur (267 patients; 7.2%), ankle sprain (175 patients; 4.7%), and shoulder dislocation (144 patients; 3.9%).

In contrast, the most common snowboarding-related injuries were wrist fractures, such as distal radius fracture (925 patients; 13.5%), followed by laceration and contusion of the head and face (596 patients; 8.7%), shoulder dislocation (511 patients; 7.5%), fracture of the clavicle (334

Table 1. Types and sites of skiing injuries over 18 years (December 1996–March 2014)

Site/Injury		Fracture	Sprain	Laceration/Contusion	Bruise	Dislocation	Other	Total		%
Head/Face		4	0	312 ②	54	1	11	382	382	10.3%
Upper limb	Clavicle	110 ⑦	3	0	4	30	0	147	865	23.4%
	Shoulder/blade	27	30	1	46	144 ⑤	5	253 (6.8%)		
	Humerus	107 ⑧	0	2	11	3	0	123		
	Elbow	8	15	2	12	6	3	46		
	Forearm	11	1	4	5	0	0	21		
	Wrist	63	17	6	2	0	1	89		
	Finger	61	57	37	14	14	3	186		
Trunk	Lower back/spine	40	92 ⑩	7	78	2	6	225	329	8.9%
	Chest/abdomen	64	0	4	34	0	2	104		
Lower limb	Femur	39	26	12	28	5	4	114	2,127	57.4%
	Knee	142 ⑥	861 ①	33	67	8	53	1,164 (31.4%)		
	Lower leg	267 ③	87	78	77	0	42	551 (14.9%)		
	Ankle	96 ⑨	175 ④	0	1	7	5	284 (7.7%)		
	Toe	2	5	0	2	3	2	14		
	Total	1,041	1,369	498	435	223	137	3,703	3,703	
	%	28.1%	37.0%	13.4%	11.7%	6.0%	3.7%			100.0%

①–⑩, Order of incidence of the top 10 skiing-related injuries

Table 2. Types and sites of snowboarding injuries over 18 years (December 1996–March 2014)

Site/Injury		Fracture	Sprain	Laceration/ Contusion	Bruise	Dislocation	Other	Total		%
Head/Face		10	0	596②	103	1	4	714	714	10.4%
Upper limb	Clavicle	334④	12	0	6	149	0	501	3,625	52.9%
	Shoulder/blade	32	77	1	132	511③	8	761 (11.1%)		
	Humerus	272⑨	2	0	15	0	0	289		
	Elbow	138	251	11	48	181	3	632 (9.2%)		
	Forearm	59	1	30	21	0	0	111		
	Wrist	925①	148	9	32	6	3	1,123 (16.4%)		
	Finger	71	42	60	19	13	3	208		
Trunk	Lower back/spine	293⑦	147	22	288⑧	2	4	756 (11.0%)	1,091	15.9%
	Chest/abdomen	196	2	4	124	1	8	335		
Lower limb	Femur	16	20	8	27	9	1	81	1,428	20.8%
	Knee	9	298⑥	44	63	3	9	426		
	Lower leg	72	39	244⑩	45	0	13	413		
	Ankle	115	327⑤	0	6	3	1	452		
	Toe	29	19	1	4	0	3	56		
	Total	2,571	1,385	1,030	933	879	60	6,858	6,858	
	%	37.5%	20.2%	15.0%	13.6%	12.8%	0.9%			100.0%

①–⑩, Order of incidence of the top 10 snowboarding-related injuries

patients; 5.0%), and ankle sprain (327 patients; 4.8%).

Among the 61,378 patients with ski-related injuries treated during the 40-year period from December 1957–March 1997 in our clinic, there were 43,263 patients (70.5%) with lower limb injuries, 8,587 patients (14.0%) with upper limb injuries, 7,121 patients (11.6%) with injuries to the head and face, and 2,407 patients (3.9%) with injuries to the trunk[20]. These results are comparable to those of our previous study; however, the most common site of injury was the ankle (17,141 patients; 27.8%), followed by the knee (14,451 patients; 23.5%).

For ski-related lower limb injuries, the type of injury was basically determined by whether the fall involved external rotation, internal rotation, or anterior/posterior motion of the upper body. Knee sprains caused by falls with external rotation were particularly common. In addition, although uncommon in snowboarding-related injuries, we found that lower leg fractures and thumb sprains commonly occurred.

2. Changes in injury statistics

On observing changes in the order of incidence of ski-related injuries over the 18-year period, knee sprains were ranked first at 21.5% for Period 1 (December 1996–March 2002), 24.1% for Period 2 (December 2002–March 2009), 26.8% for Period 3 (December 2009–March 2012), and 26.0% for the most recent Period 4 (December 2012–March 2014), peaking in Period 3. As the most common site of ski-related injury, and as the next most common type of injury following sprains, knee fractures, such as tibial plateau fractures and fractures of the intercondylar eminence of the tibia, were common at 3.1% in Period 1 (December 1996–March 2002), 5.0% in Period

2 (December 2002–March 2009), 4.2% in Period 3 (December 2009–March 2012), and 4.1% in Period 4 (December 2012–March 2014), peaking in Period 2 (December 2002–March 2009). When knee sprains and knee fractures were considered together, their incidence was 31.0% in Period 3 (December 2009–March 2012), exceeding the 30% overall incidence (Table 3).

Amongst the 61,378 patients with ski-related injuries treated in our clinic over the previous 40-year period from December 1957–March 1997, knee sprains were the most common injury type (12,814 patients; 20.9%). However, this injury type only affected around 20% of patients, with hardly any knee fractures observed (344 patients; 0.6%).

Table 3. Top 10 most common skiing injuries (December 1996–March 2014)

	18 years (Dec 1996–Mar 2014)		Period 4 (Dec 2012–Mar 2014)		Period 3 (Dec 2009–Mar 2012)		Period 2 (Dec 2002–Mar 2009)		Period 1 (Dec 1996–Mar 2002)	
Order	Injury	%	Injury	%	Injury	%	Injury	%	Injury	%
1st	Knee sprain	23.3%	Knee sprain	26.0%	Knee sprain	26.8%	Knee sprain	24.1%	Knee sprain	21.5%
2nd	Head/facial laceration/ contusion	8.4%	Lower leg fracture	10.1%	Lower leg fracture	7.2%	Head/facial laceration/ contusion	8.2%	Head/facial laceration/ contusion	10.2%
3rd	Lower leg fracture	7.2%	Lower leg sprain (gastroc. rupture)	6.4%	Clavicular fracture	6.2%	Lower leg fracture	8.1%	Lower leg fracture	6.2%
4th	Sprained ankle	4.7%	(Eq 4th) Knee joint fracture	4.1%	Humerus fracture	5.3%	Knee joint fracture	5.0%	Sprained ankle	5.3%
5th	Shoulder dislocation	3.9%	(Eq 4th) Head/facial laceration/ contusion	4.1%	(Eq 5th) Head/facial laceration/ contusion	4.4%	Sprained ankle	4.4%	Shoulder dislocation	4.3%
6th	Knee joint fracture	3.8%	Clavicular fracture	3.5%	(Eq 5th) Sprained ankle	4.4%	Lower leg sprain (gastroc. rupture)	3.9%	Knee joint fracture	3.1%
7th	Clavicular fracture	3.0%	Spinal sprain	3.2%	Knee joint fracture	4.2%	Ankle fracture	3.7%	Knee joint, Other	2.7%
8th	Humerus fracture	2.9%	(Eq 8th) Shoulder dislocation	2.9%	Shoulder dislocation	3.9%	Shoulder dislocation	3.4%	Lower back bruising	2.6%
9th	Ankle fracture	2.6%	(Eq 8th) Wrist fracture	2.9%	Lower leg sprain (gastroc. rupture)	3.0%	Humerus fracture	3.2%	Lower leg bruising	2.4%
10th	Spinal sprain	2.5%	(Eq 8th) Sprained ankle	2.9%	(Eq 10th) Wrist fracture	2.3%	Clavicular fracture	2.9%	(Eq 10th) Humerus fracture	2.3%
					(Eq 10th) Lower leg bruising	2.3%			(Eq 10th) Knee joint bruising	2.3%
					(Eq 10th) Thoraco-abdominal bruising	2.3%				
	Knee sprain + knee joint fracture	27.1%	Knee sprain + knee joint fracture	30.1%	Knee sprain + knee joint fracture	31.0%	Knee sprain + knee joint fracture	29.1%	Knee sprain + knee joint fracture	24.6%

gastroc, gastrocnemius; Eq, equal

3. The mechanism underlying injury to the knee

When sporting events were observed using a video camera, we found that turns had changed from the previous technique that used a high braking element to a turn that used a high accelerator element. Skiers using conventional alpine skis up to the first half of the 1990s used a turning technique whereby the center of gravity was shifted while applying alternating weight to each leg and breaking the angle of attack in a rhythmical pattern, with the lower body leaning inward to the turning curve and the upper body leaning outward of the turning curve. Alpine skiing in the latter half of the 1990s involved a turning technique whereby the knees were placed in deep flexion with the upper body lowered, and at the start of a turn, the legs were angled to lean inside the turning curve, intentionally applying one's weight there. Then, by applying the balance of the weight, using external force, such as centrifugal force/centripetal force, the skis deflected, thereby carving the surface of the snow while creating a foothold. Thus, the turning technique underwent a major change, evolving into carving skiing. Although this carving technique allows for faster runs, in the second half of the turn, such as in "uphill turns", a backward-leaning posture is adopted without the upper body keeping up, which often leads to falls or near-falls from which the skier recovers but requires medical examination for stress at sites around the knee, such as in the quadriceps femoris muscles (Fig. 1).

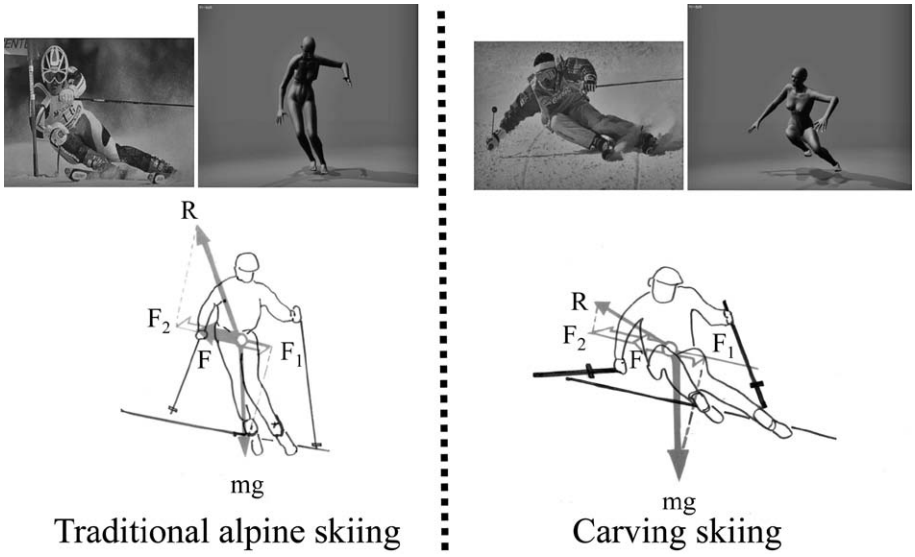

Fig. 1. Comparison between traditional alpine skiing and carving skiing
The two forces exerted on the skier at the second half of a turn are gravity (mg) and resistance (R).
The components of the rotational motion on the slope are (1) the gravity component of the slope: $F_1 = mg \sin\alpha \cos\beta$ and (2) the resistance component of the slope: F_2.
The components affecting the rotational force are $F = F_2 - F_1$.
Because F_1 and F_2 are in opposite directions, F_1 works against the rotation and greater snow surface resistance is required to secure the rotational force, F.
Greater leg strength is required in the second half of the turn.

Discussion

1. The mechanism and morphology of ski-related injuries

Ski-related injuries are closely related to the development of ski equipment. Around 1965, hard, deep plastic ski boots (chemical boots) appeared; subsequently, in 1978, leather ski boots were entirely replaced by chemical boots, which held and protected the ankles securely, thereby minimizing ankle injuries for 20–30 years up to 1990. However, there has been an increase in fractures in the middle of the tibia, called boot top fractures[21], which occur because the upper part of the chemical boot acts as a point of bearing during anterior falls, resulting in increased load on the knees rather than the ankles.

Furthermore, with the decline in the number of skiers from around 1996, snowboarders called for managerial improvements in ski resorts to enable snowboarding on all runs. However, having snowboarders and skiers on the same runs led to some of the changes in the 18-year study period, including the mechanism and morphology of ski-related injuries, as well as injuries caused by collisions. Although snowboarding-related injuries vary highly along with the type of sporting event, the occurrence of ski-related injuries is relatively standard and can essentially be broadly categorized into the following two categories: (a) 'falls', injuries caused by an indirect external force via ski equipment; and (b) 'collisions', injuries caused by a direct external force. The type of injury is basically determined according to the morphology of the injury. Specific injuries also remain, such as skier's thumb (injury to the thumb metacarpophalangeal joint accessory ligament on the ulnar side) classically caused by falling while holding ski poles[22] and shoulder joint dislocation[23] (Table 4).

2. Changes in injury statistics

As mentioned earlier, a clear increase has been observed in the incidence of knee sprains over the past 18 years (December 1996–March 2014) compared with the earlier 40-year period (December 1957–March 1997). Detailed investigation of changes in the past 18 years, divided into four periods, also showed that not only knee sprains but also knee fractures have increased, with injuries to the knee overall continuing to increase. Injuries to the knee rapidly increased to a peak in 2012, and therefore, the mechanism underlying injury to the knee should be examined in detail. Indeed, it is assumed that not only the developments in ski equipment, such as skis and ski boots, but also the associated changes in skiing styles has led to skiers adopting knee positions that are more prone to injury. Our 18-year questionnaire survey of patients with ski-related injuries also identified that most patients who suffered from ski-related injuries used short skis rather than long skis, which supports the notion that the popularization of carving skis in Japan has led skiers to adopt a knee position that is highly prone to injury.

3. The mechanism underlying injury to the knee

Carving skiing started in 1999 and became popular in Japan following the 2002 Salt Lake City and 2006 Torino Winter Olympics. In addition, skiing styles underwent a marked change from

Table 4. Mechanism and morphology of skiing injuries

Mechanism of injury			Types of injury
Injury due to indirect external forces	1. Lower limb injury	a) External rotational fall	Sprained ankle (inferior tibiofibular joint, deltoid ligament) Lateral malleolus fracture External rotation lower leg fracture Knee sprain (MCL)
		b) Internal rotational fall	Sprained ankle (ATFL) Medial malleolus fracture Lower leg internal rotational fracture
		c) Forward fall	Lower leg boot-top fracture[21] Fracture of the anterior border of the inferior extremity of the tibia Rupture of the Achilles tendon Dislocation of the peroneal muscle tendon
		d) Backward fall	Fracture of the posterior border of the inferior extremity of the tibia
	2. Trunk injury (falls)		Compression fracture of spine Coccygeal fracture Cervical dislocation/fracture
	3. Upper limb injury		Skier's thumb[22] Anterior dislocation of the shoulder[23]
Injury due to direct external forces	1. Injury in a fall		Laceration/contusion, bruising, fracture, dislocation
	2. Injury in a collision		Various

traditional alpine skiing to carving skiing.

The technique of carving skiing requires the tibia to be pulled further forward, thereby increasing the number of injuries to the ACL. In particular, carving skiing requires: (1a) an inward-leaning posture with the lead of the inner ski to generate force toward the internal turn and to counter the centrifugal force; and (1b) an inward-facing posture to synchronize the outer ski to the rotating inner ski. At this time, (2) the inner knee is partially loaded to the ski in a low position, deeply bent to maintain the center of gravity, and slightly rotated externally. Under the combined conditions of (1) and (2), the knee joint is unstable, and the ACL is tensed, amplifying the risk of ACL injury or tibial plateau fracture when the flexion or external rotation is increased (Fig. 1).

Pujol *et al*[24] reported that, according to the statistics of the past 25 years, the number of ACL injuries in alpine skiers has not declined and that the prevention of these injuries is an incredibly important goal. Hansom and Sutherland[25] discussed trauma prevention in skiers and snowboarders and reported that the most commonly described significant ski injury was ACL rupture, whereas in snowboarding it was wrist fracture. In addition, skiers were more likely to improve fitness levels before going onto the slopes, whereas crossover riders (both skiing and

snowboarding) were more likely to take lessons.

To summarize the above, the development of ski equipment, such as carving skis, has led to many knee sprains and ski-specific injuries. The incidence of knee sprains has increased over the 18-year period of December 1996–March 2014 compared to the earlier 40-year period from December 1957–March 1997. In addition, there has also been an increase in the incidence of knee fractures over the past 18 years, indicating a continued increase in the incidence of knee injuries overall. Thus, as well as developments in ski equipment, the associated changes in skiing style have led to skiers to adopt a knee position prone to injury. With the recent change from conventional alpine skiing to carving skiing, the knee joint is unstable and the ACL tensed, thereby increasing the risk of ACL injury or tibial plateau fracture when the flexion or external rotation is intensified. Thus, with the development of ski equipment, we have witnessed injuries characteristic to skiing, with a subsequent increase in knee injuries.

We will further investigate the prevention of knee injuries caused by carving skiing, including the acquisition of a greater understanding of the winter sport population.

Conclusions

Of the 10,561 patients who suffered skiing- and snowboarding-related injuries over the 18-year study period, we investigated 3,703 patients with ski-related injuries. With developments in ski equipment, we found that injuries characteristic to skiing increased, with a further increase in knee injuries. We aim to further investigate the prevention of knee injuries caused by carving skiing.

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The study was based on anonymized data of injured patients obtained from the Showa University, Ishiuchi Ski Clinic, and Japan Snowboarding Association (JSBA).

Conflict of interest disclosure

The authors declare no conflict of interest.

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